INTRODUCTION

The first indications of neutralization of the optical power of corneal curvature by means of the immersion of the eye in a liquid can be found in the writings and sketches of *Leonardo da Vinci*. This author is sometimes credited, because of this, with the discovery of the principle of contact lenses, or even of their actual invention.

Certain drawings showing immersion of the face or the orbital region within hemispheric structures, glass cups filled with water, could even make you believe, if you append appropriate legends, that *Leonardo da Vinci* was aware of, or understood, neutralization of the optical power of the cornea in a liquid. These sketches, diagrams, drawings and texts are found in Manuscripts D and K of Paris, and in the Codex atlanticus of Milan.

By means of a painstaking and careful interpretation of the work of *Leonardo da Vinci*, I will attempt to discover if the neutralization of the corneal dioptic power, in the strict sense, has in fact been described, researched, or utilized and if *Leonardo* had taken cognizance of its significance and interest.

I propose, as a **first step**, to reproduce the texts and the illustrations concerned and to provide from these the most objective possible translation and analysis, taking into account the difficulties of *Leonardo's* prose, by placing them in the context of the manuscripts from which they are taken and from the work of *Leonardo*. In this way, we will view:

- Folios 3 verso and 7 verso of Manuscript D;
- Folios 118 verso and 119 verso of Manuscript K;
- Folio 222 recto/a of the Codex atlanticus.

As a **second step,** I will place the optics, the anatomy, and the ocular physiology in the context of the knowledge of his time. That will take us towards a succinct historical retrospective of the transition from the heritage of Greece to the medieval authors.

Finally, I will challenge these observations using the criteria of the corneal curvature's optical neutralization and the properties of contact lenses. I will investigate these texts and drawings in order to determine if they provide arguments in favor of an earlier description of one or more principles of corneal dioptic power neutralization or contact systems, as certain authors have suggested.

1 – Source Documents

The three texts usually quoted in connection with corneal optical neutralization or contact lenses are extracted from:

- Manuscript D, in particular from folios 3 verso and 7 verso;
- Manuscript K, in folio 118 verso;
- Codex atlanticus, in folio 222 recto.

1.1 – Manuscript D from Institut de France

The Original of Manuscript D

The original of Manuscript D is said to be preserved in the *Bibliothèque Mazarine* of the *Institut de France*, (23, Quai Conti, Paris). In fact, the manuscript has been placed, for security reasons, in the safes of the *Banque de France*. Researchers are directed either to photographic copies, or to the facsimiles of *Corbeau and Toni* (1964). The latter are in color and of very high quality. They are the ones that I have used.

This Manuscript is handwritten by the author, to judge from its left-handed mirror writing. It is a fascicule of five double pages sheets, which, folded in two, comprises ten folios in 220 x 180 mm format. This is enclosed in four protective folios made from two folded sheets. (1)

The Pagination of Manuscript D

The pagination is in normal, non-mirror handwriting and in progressive order from 1 to 10 in the right superior corner of the front of each of the folios. *Ravaisson-Mollien* (1883) attributed this to the master's hand, but this has been contested (*Corbeau* 1964, *Strong* 1967). The order of the pagination does not in fact correspond to the continuity of sequences linking corresponding arguments, or to that of the watermarks of the paper of the folios. According to these authors, *Leonardo* would not have used a pre-cut work book, but rather large complete sheets of a format double the size of those used today and after folding them in four, he would have used the surfaces thus obtained for writing on. The person carrying out the pagination would have later cut the sheets horizontally, and then would have marked the half folios. These mix-ups of the original pagination by the compiler are not without consequence for our understanding and interpretation of the text and I will take account of that aspect in my analysis.

The Subject Matter of Manuscript D

Manuscript D reveals the ideas of *Leonardo* on the anatomy of the eye in relation to the formation of images and visual perception. Thus, it concerns a specialized treatise, or, more probably part of a specialized treatise. Using a schematized diagram of an artificial eye, he converts the visual organ into a mechanical structure which allows the observation of the progress of the rays from the cornea as far as the optic nerve, while taking into

1. The writing was done on two large-sized sheets that were cut down and paginated later without taking their original arrangement into consideration.

consideration the inversion of those rays in a dark chamber and at the same time offering various hypotheses to explain their correction from inverted to upright images.

The Dating of Manuscript D

We do not have any date or allusion permitting us to determine the time of the writing of Manuscript D. According to the specialists, we would be considering a late work set in the period of time between 1505 and 1516, probably between 1513 and 1516 (*Corbeau* 1964, *Strong* 1967).

The Study Procedure

After enlargement and correction of the mirror writing, I deciphered, analyzed, and translated the text from the old Tuscan dialect. This was not always easy, as *Leonardo* used no period or comma to separate one sentence from another. Capital letters are only placed at the beginning of a chapter, while the words often run into one another or are abridged. The style is heavy and the vocabulary sometimes ambiguous. I will return several times to these vocabulary problems, which are important for interpretation of the document (2).

Comparison to existing Translations

For this study, I have compared my translation with the classical translations of *Raivaissen-Mollien* (1883) and of *Corbeau* into French (1964), of *Toni* into Italian (1964), and of *Ferrero* (1952) and *Strong* (1967) into English. I refer to translations made by linguists or art historians who typically did not always know how to express accurately the nuances of ocular anatomy or ophthalmic optics. This explains the variations of the different translations and the frequent divergences in the interpretations of these passages.

Terminology	
Old terms	Contemporary equivalents
By experience	Universally recognized
Eidola,	Images
Luce, sphera luce	Cornea, anterior chamber, pupilla, anterior segment of the eye
Simulacra, similitudes	Images
Species	Rays
Sphera luce	See luce
Visual virtue	Visual sense as transmitted from eye to brain (cerebral ventricle)

2. The orthography is capricious and confirms the impression of "uomo sensa lettera" (an unlettered man), which was attributed to Leonardo.

1.1.1 – Folio 3 verso of Manuscript D

A - The Structure of Folio 3 verso

(Figures 1 – 1 & 1 - 2)

Folio 3 verso of Manuscript D carries the general title *"Occhio umano" (On human eye)*. It is divided vertically into two sections:

1. The first is the principle section and occupies two thirds of the width and comprises two paragraphs of superposed text, separated by a diagram and legends;
2. The second is in the margin of the foregoing and takes in, from the top downwards, a schematic diagram of the artificial eye and three schematic eye diagrams accompanied by their legends.

The **upper** part of the texts takes the form of sub-titles:

"How to perform an experiment to demonstrate how the visual virtue employs the instrument of the eye."

"Del fare speriçtia come la virtu visiua adoÞera lo sstrumçto dell occhio"

It describes the artificial eye experiment and its interpretation. Two drawings are found in the margin, the first of an artificial eye, and the second of a schematic eye.

The **lower** part of the texts also takes the form of sub-titles:

"How the specie give themselves to the visual virtue with two cross-overs by necessity."

"Come le spetie si dãno alla uirtu visiua con due intersegationi Þ necessita"

It is less homogeneous than the preceding, because the text is interspersed between the three schematic diagrams and their legends.

B - The Sequences of Folio 3 verso

Folio 3 verso can be divided into localized sequences, as follows:

1. As a function of their revealed position in centimeters with reference to the upper margin of the folio, (the total height of the folios is 22 cm),
2. As a function of their position:
   - In the '*textual*' part (sequences T1 to T9);
   - In the '*marginal*' part (sequences M1 to M6).

I propose to describe them, after division and numbering, from above down, as follows:

1. The general title (from 0 to 1 cm) **T 1**

2. An homogeneous text (from 1 to 11.50 cm), comprising the following elements:

- a sub-title (from 1 to 2 cm) **T 2**
- a first sequence of text (from 2 to 7cm) **T 3**
- a sketch of an artificial eye, situated in the margin (from 2 to 7 cm) **M 1**
- a note in the margin, beside the previous sketch (from 5.5 to 7 cm) **M 2**
- a second textual sequence (from 5.50 to 11.50cm) **T 4**

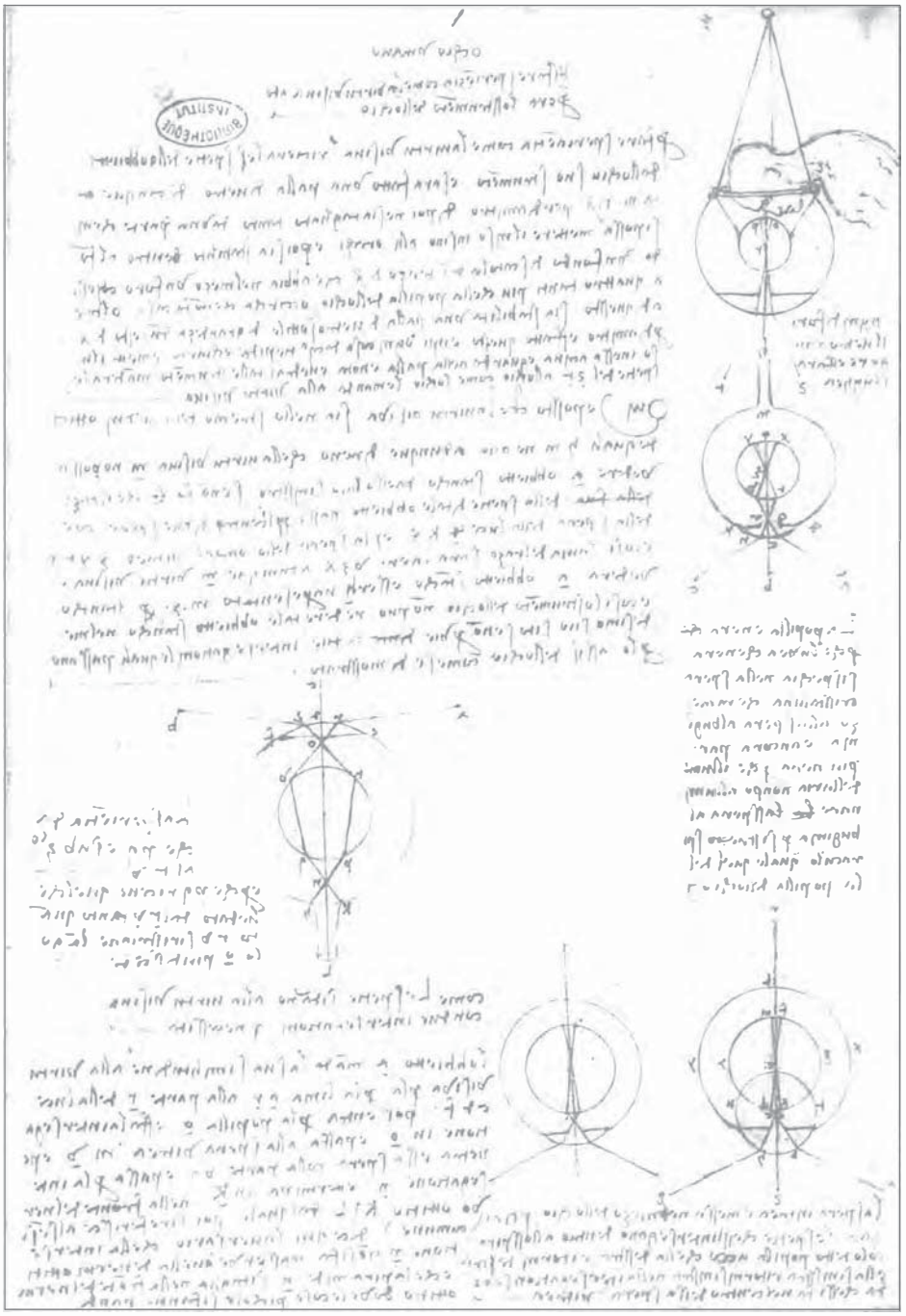


Figure 1 - 1

Leonardo da Vinci, Manuscript D, folio 3 verso.
(original dimensions: 220 x 180 mm).

The mirror writing is typical of Leonardo's writings. To read this requires reversal of the mirror writing. The text contains neither periods nor commas to mark and separate the beginning from the end of sentences. For the present analysis, the document is catalogued in two parts:

1.) **on the left,** a main section (the sequences of texts T 1 to T 9), comprising one title, one sub-title, and two parts separated by a central drawing and its legends;

2.) **on the right,** a margin (the sequences M 1 to M 6), consisting of the schematic diagram of an artificial eye and three eye-sketches with their legends.

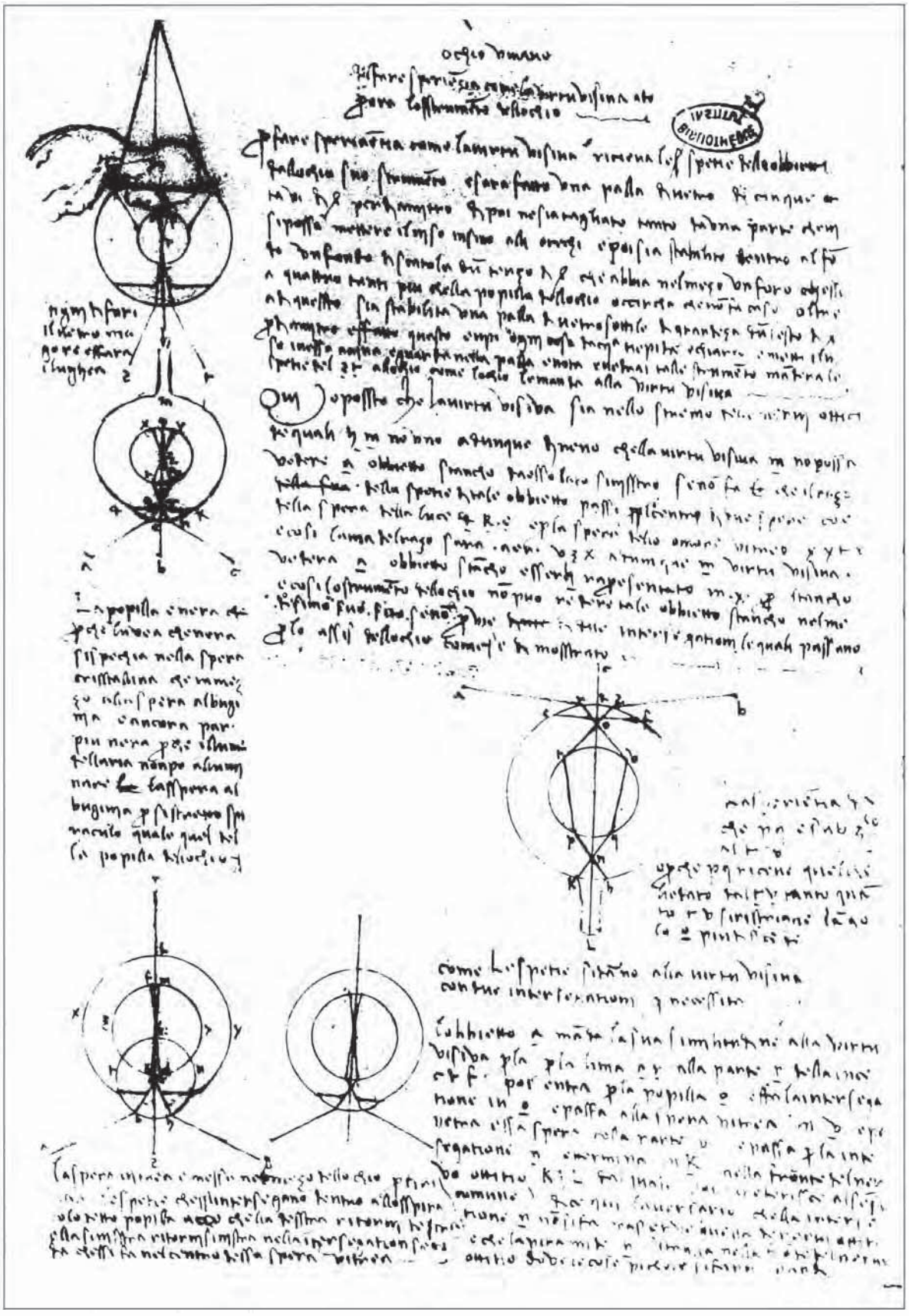


Figure 1 - 2

Leonardo da Vinci, Manuscript D, folio 3 verso.

The mirror writing is reversed, in order to facilitate deciphering the text.

- a sketch of the schematic eye, situated in the margin (from 7 to 10.50cm) **M 3**

3. A central part (from 11.50 to 16.50 cm) formed from the following elements:

- a text in the margin (from 10.50 to 16.50 cm) **M 4**
- a drawing of the schematic eye, in central position (from 11.50 to 16.50 cm) **T 5**
- a first lateral text in the central drawing (from 13.5 to 15 cm) **T 6**
- a second lateral text in the central drawing (from 15 to 16.5 cm) **T 7**

4. A lower part (from 16.5 to 22 cm) with:

- a sub-title (from 16.5 to 17.5 cm) **T 8**
- a text (from 17.5 to 22 cm) **T 9**
- two diagrams of the schematic eye in the margin (from 16.5 to 20 cm) **M 5**
- a text in the margin under the diagram (from 20 to 22 cm) **M 6**

TITLE (T1) *(from 1 cm to 2 cm)*
(Figure 1-3)

"On human eye"

"Ochio umano"

This same title, of "*occhio umano*", is found at the top of folios 3 recto and 8 recto, which leads me to suppose that the writing of these occurred at the same approximate date. For *Corbeau* (1964) and for *Strong* (1967), *Leonardo* would have started with folio 3 verso and continued with folio 8 recto, and then finished with folio 3 recto. The folio 3 verso itself refers to the experiment of the instrument of the eye, that was announced in folio 2 recto and would have been written following this last reference.

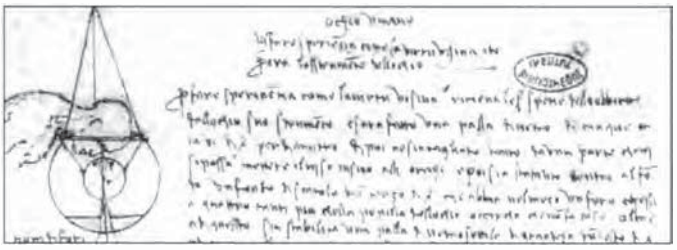


Figure 1 - 3

Leonardo da Vinci, Manuscript D, folio 3 verso. (T 1 & T 2).

Title (T 1) "ochio umano" (On human eye).
Sub-title (T 2) "del fare sperietia come la virtu visiua adopera lo sstrume dell ochio" (How to perform an experiment to demonstrate how the visual virtue employs the instrument of the eye).

SUB-TITLE (T2) *(from 1 cm to 2 cm)*
(Tableau 1 – 1)

"How to perform an experiment demonstrating how the visual virtue employs the instrument of the eye".

"Del fare speriçzia come la virtu visiua adoƀera lo sstrumçto dell ochio"

Leonardo announces that he will explain the formation of the *visual virtue* inside the eye that he likens to an optical instrument. The reference to the *visual virtue* constitutes a vestige of the theory of extramission that is a product of the Greco-Roman concept of the sense of vision, which results from an active force coming from the eye of the observer. The

concept of the eye behaving, as an active element in the process of vision was further expanded in certain quarters at the end of the 15th century. *Leonardo* will abandon the theory of extramission of visual virtue in his later manuscripts of the last period; only to bring it up again in his discussions contained Manuscript D. *(Figure 1 – 3)*

In the context of folio 3 verso, as announced in this sub-title, *Leonardo* no longer gives the *Galenic* meaning of extramission to the *visual virtue,* but considers it as a sensation or perception of vision destined to be transmitted to cerebral structures.

In referring to *"the instrument of the eye" ("le sstrumento dell ochio"), Leonardo* is innovating, as he attributes the role of an optical instrument to the eye, in the interior of which, the images of the objects (*the species)* are transformed into a visual sensation, the *virtu visiua (visual virtue).*

First Part of the upper Text (T 3) *(from 2 cm to 7 cm)*
(Figure 1-4)

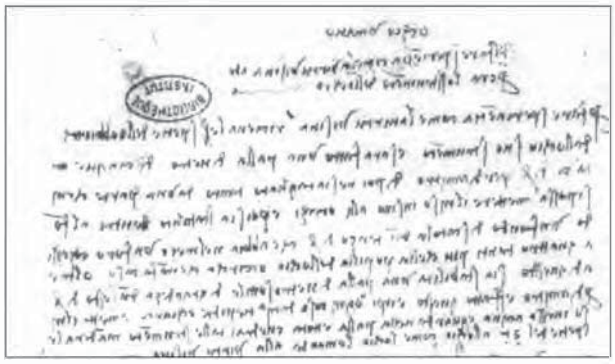


Figure 1 - 4

Leonardo da Vinci, Manuscript D, folio 3 verso. (T 3).

First part of the upper paragraph (T 3).

In this passage, Leonardo explains the construction of the artificial eye, reproduced in the margin, where a human head is immersed in such a way that the human eye is situated in the area of the optic nerve of the artificial eye.

"In order to perform an experiment that demonstrates how the visual virtue receives the specie of the objects by the eye, its instrument, make a globe of glass of 5/8th of a braccia (3) in diameter, and then cut off a part of sufficient size in order to put the face in it down to the ears. Then fix (4) at the bottom of it a bottom of a box, a third of a braccia in size, in the middle of which will be pierced a hole, four times larger than the pupil of the eye or thereabouts (5), it matters little. In addition, fix a sphere of fine glass (6), of a diameter of a sixth of a braccia in width. That done, fill the whole (7) with tepid (8) and clear water and put the face in this water, look into the sphere and observe how such an instrument dispatches the species of .s t. to the eye, just as the eye sends them to the visual virtue".

"Þ fare sperinçtia come la uirtu visiua ricieua le spetie delli obbietti dall ochio suo strumçto e sara fatto vna palla ò uetro ò cinque ottavi ò â per ðamjtro ò poi ne sia tagliato tanto da vna parte che uj si possa mettere

3. "braccia", measure corresponding in principle to the length of two arms well extended (about 1,60 meter). The braccio of Leonardo corresponds more closely to an 'ell' (about 0,60 to 0,70 meter). See note 53.
4. "stabilito, stabilita", 'fix', 'fix by a suspension' (according to Corbeau, 1964).
5. "o circha", word deleted by Corbeau (1964).
6. "uetro sottile", subtle glass, which is of fine quality and thin, according to the current meaning. But under the circumstances, pure or fine glass would seem to be the more acceptable term, because the context appears to be linked more to the quality of the material of the sphere than to its thickness. In folio 7 verso, the sphere of the crystalline lens is compared to a crystal ball. An empty sphere with thin wall filled with air would not have produced the effect of density attributed to the vitreous humor and the crystalline lens.
7. "ognj cosa", 'everything', (according to Corbeau, 1964).
8. "acq terpida", 'lukewarm water', which is allegedly lighter than cold water: the refraction produced by the interface between the lukewarm water and the glass would cause the rays of light to deviate towards the normal.

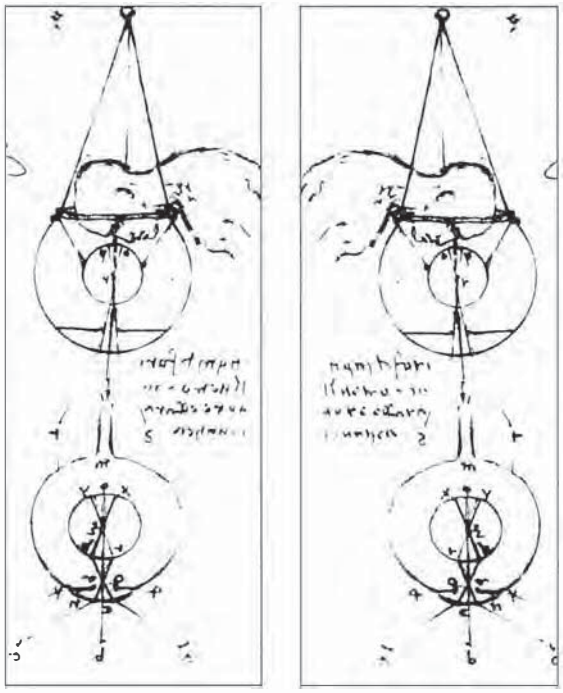
il ujso insino allj orechi e poi sia stabilito dentro al fõdo vn fondo ò scatola d ù terzo ò â che abbia nel mezo vn fòro che ssia quattro tanti piu che lla popilla dell ochio o ccircha che nô fa caso oltre a ò quessto sia stabilita vna palla ò uetro sottile ò grandeza d ù sesto ò â Þ ðamjtro e ffatto questo enpi ognj cosa d acq tiepida e chiara e metti il ujso in essa acqua e guarda nella palla e nota e uedrai talle strumçto mãdera le spetie del .s t. all ochio come l ochio le manda alla virtu visiua."

We are considering *Leonardo's* proposal to construct an artificial eye according to the drawing (M 1) in the margin. This structure would consist of a suspended glass sphere filled with water. In its center, a glass sphere would be fixed in a stable fashion and representing the crystalline lens. A screen representing the iris diaphragm with pupillary aperture is fixed in its lower third. A human face would be submerged therein right up to the ears, in such a way that the eye of this observer is situated in the area of the optic nerve. (*Figure 1 - 5*)

The conclusion indicates nicely, that the glass sphere, that represents the crystalline lens, receives images of objects on its posterior surface, where the optic nerve perceives these and sends them to the common sense.

Schema of the artificial Eye (M 1)
(in margin, from 2 cm to 7 cm)
(Figure 1 - 5)

This drawing is, without doubt, the schematic representation of the artificial eye as described below in the text T 3. It is very unlikely that *Leonardo* actually constructed such an instrument, which would not in any event have given the intended result, i.e., the projection of an image on the bottom of the glass sphere, where it could have been perceived by the eye of an observer placed in the position of the optic nerve.



A Original *B Reversed*

Figure 1 - 5

Leonardo da Vinci, Manuscript D, folio 3 verso. Upper part of the margin.

Schematic diagram of an artificial eye (M 1), text (M 2), and schematic eye (M 3).

The diagram of an artificial eye (M 1), illustrates the adjacent text (T 3):

The upper half of a glass globe is cut out and a diaphragm is placed on the bottom. A glass sphere is positioned in the center of the globe and the globe is filled with tepid water.

By submerging the face inside this globe and looking at the glass globe, one can "observe how such an instrument dispatches the species of (s t.) to the eye, just as the eye send them to the visual virtue".

The discussion concerns an antic conception of visual perception by the eye: the species pass on, or in, the crystalline lens, represented by the inside glass sphere, whence these are captured by the optic nerve (positioned in the area of the eye of the submerged head, and the optic nerve sends these in turn to the visual virtue.

(The text M2 and the drawing of the schematic eye M3 are analyzed in figures 1 - 6 and 1 - 7).

This sketch has been used many times, but erroneously, for attributing to *Leonardo* the priority of the description of a contact lens. According to these mistaken interpretations, the diagram would represent a neutralization of the corneal refraction by immersion in a liquid and the substitution of a new optical element for the refractive power thus neutralized. Submerging the head in water certainly

neutralizes the corneal dioptric power, but *Leonardo* does not evoke this function, either in the folio, or in any other of his manuscripts. The proposed construction, starting from two spheres of concentric glass, has no connection with a contact glass. Neither the title T 2, or the texts T 3 and M 2, or the neighboring diagram M 1, are in favor of a contact device.

Note in the Margin of the Diagram (M 2) *(from 5.5 cm to 7 cm)*
(Figure 1 - 6)

"Hold outside the larger glass and you will make the uvea."

"Tignj ò fori il uetro magore e ffara i l ughea"

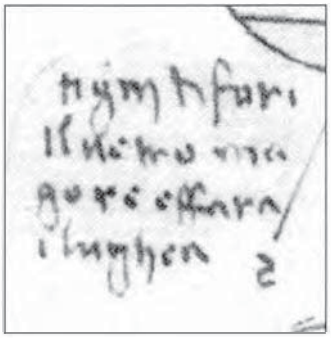


Figure 1 - 6

Leonardo da Vinci, Manuscript D, Folio 3 verso (M 2).

A note in the margin of the artificial eye (image reversed).

Text: "tignj di fori il uetro magore e ffara i l ughea" (Hold outside the larger glass and you will make the uvea.)

This text is positioned below and lateral to diagram M 1.
The glass globe representing the artificial eye is not opaque to light. In order to liken the eye to the camera obscura, *Leonardo* must shield his instrument from light in the same way as the uvea (choroid) shields the interior of the eye from light. He proposes to simulate the darkness of the uvea by surrounding the glass globe with hands. Would it not have been simpler and more efficacious to smear the glass globe with black paint or with lead, as he suggested in folio 7 verso?

The placing of a black coat around the glass globe is to come near to the idea described by *Leonardo*, in folio 7 verso that the uvea acted like a mirror, its dark part representing the coating, It is possible, that this inscription in the margin of the diagram M 1 will have been added at the time of a rereading, when *Leonardo* was interested in the uveal theory, which he described precisely in folio 7 verso.

Diagram of a schematic Eye (M 3) *(in margin, from 7 cm to 10.5 cm)*
(Figure 1-7)

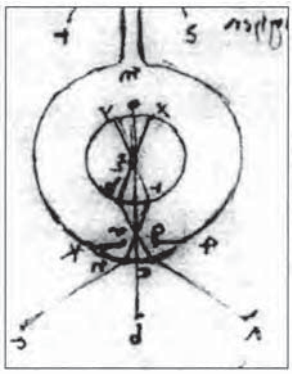


Figure 1 - 7

Leonardo da Vinci, Manuscript D, Folio 3 verso (M 3).
Drawing of a schematic eye under the figure of the artificial eye M1.

Illustration of the first explanation given by Leonardo in order to explain the intraocular conversion of inverted images to upright.

After an initial crossing of the rays at the center of the pupil (in the sphere of the luce), a second reversal of these occurs at the center of the crystalline lens. Thus, the image would arrive as an upright image at the back surface of the crystalline lens. The optic nerve, would capture this upright species and send it into the visual vertue.

This diagram completes and resumes, at the same time, the adjacent text T 4 and the diagram M 1 of the artificial eye within which it is also interspersed.
We are concerned with *Leonardo's* first proposal, which he enunciated in order to explain the intraocular conversion of inverted images to upright images. After the first crossing of the rays in the center of the pupil, in the sphere of the *luce*, a second inversion of the image would be produced in the center of the crystalline lens. Thus, the image of the object would

arrive upright at the posterior surface of the crystalline lens. The optic nerve, would seize on this upright image, and conduct it to the common sense.

Text in the Margin (M 4) *(in margin, from 10.5cm to 16.5 cm)*

"The pupil is black because the uvea, which also is black, reflected itself in the crystalline sphere, which is in the middle of the albugineous sphere, which itself appears still more black because the light of the air cannot illuminate (9), *through an aperture as narrow as the pupil of the eye."*

"La popilla e nera Þche l uvea ch e nera si spechia nella spera crisstallina ch e in mezzo alla spera albuginja e ancora par piu nera Þche il lume dell aria non po allumjnare la sspera albuginja Þ si stretto spiraculo qual e quel della popilla dell ochio."

The question of the blackness of the pupil is a digression with reference to the principal subject of this folio. It is possible that it came as an inspiration to *Leonardo* at the time of a rereading, after the annotation of the text M 2 on how to simulate the darkness of the uvea. The reflection from the uvea in the crystalline lens is the object of descriptions in folio 7 verso, where the uvea acts as a mirror. *Leonardo* gives a very fair interpretation of this, by attributing the blackness of the pupil both, to the darkness of the uvea, and to insufficient illumination from the pupillary aperture. The problem of the darkness of the interior of the eye, of its illumination, and of visualization of the ocular fundus, will be resolved theoretically by *La Hire*, in 1709, two centuries later, following a communication of *Méry* to the French Royal Academy of Sciences (1704) on the submersion of a cat's eye. It will also be resolved in clinical practice, much later, by *Helmholtz*'s invention of the ophthalmoscope in 1851.

Second Part of the upper Text (T 4) *(from 7 cm to 10.5 cm)*

"Here is affirmed that the visual virtue is in the extremity of the optic nerve of which .h m n. is one, therefore, we can say that the visual virtue .m. could not detect a faint object on its left side, if it does not happen that the specie from such an object pass through the center of the two spheres, through the sphere of the luce (10) .d k e. and through the sphere of the vitreous humor .x y t v. and so the path of the rays will be .a e r. .v z x. Then .m., the visual virtue, will see the object faintly represented at the left in .x. and it is thus because thus the instrument of the eye is not able to convey such a faint object to the same place if not through the path of the two intersections (11) which pass along the axis of the eye, as demonstrated."

"Quj e possto che la uirtu visiva sia nello stremo delli neruj otticj de quali.h m n e. vno adunque ðreno che lla uirtu visiua .m. nö possa vedere .a. obbietto stancho da esso lato sinjsstro se nô fa che il razo della spetie ð tale obbietto passi Þ l i centrj ð due spere coe della spera della luce .d k e. e Þ la spera dello omore vitreo .x y t v. e cosi la uja del razo sara .a e r. v z x adumque .m. virtu visiua. vedera a obbietto stãcho esserlj repesentato in.x. stancho e cosi lo strumçto dell ochio nô puo rçdere tale obbietto stancho nel medesimo suo sito se nô Þ vie ð due intersegationj le qualj passano Þ lo assis dell ochio come s e dimosstrato"

9. "allumjnare", 'illuminate' (according to Corbeau, 1964).
10. "spera della luce", Corbeau (1964) makes an error in translating it by 'sphere of the cornea'. This does not correspond with the idea of Leonardo, who understands by 'sphere of la luce' a refractive instrument placed in front of the pupil, (see diagram M 5 of the same folio). I will return later to the various interpretations of 'luce' and of the one I have retained.
11. 'Crossing', according to Corbeau (1964).

Leonardo presents here the hypothesis that the localization of the perception of the images (the place where the species are transformed into visual virtue) would be situated in ".h m.", at the level of the optic papilla (the area in the artificial eye, where the observer's eye is placed) and not in the crystalline lens, as accepted by *Galenic* tradition.

In this hypothesis, which is illustrated by the schematic eye diagram M 3, the rays would pass through the axis of the eye, i.e. passing through the *luce* (cornea) and the vitreous humor (crystalline lens and vitreous body) and would then undergo a crossing over as they passed from the one to the other of these structures. The rays would then arrive having crossed over twice, thus finally terminating with an upright image, at the posterior surface of the crystalline lens.

The solution suggested in the artificial eye diagram M 1, with a submerged face, illustrated by the schematic eye diagram M 3, would be that the extremity of the optic nerve would detect an image of the posterior surface of the crystalline lens in the same way as the eye of the observer submerged in the artificial eye. However, *Leonardo* refrains from explaining how the extremity of the optic nerve could detect this image. One hypothesis accepted at the time of *Leonardo* was that the vitreous (albugineous humor) was prolonged inside the hollow part of the optic nerve and conducted the visual sense to the cerebral ventricles.

Diagram of a schematic Eye (T 5)
(central part, from 11.5 cm to 16.5 cm)

By means of this schematic eye diagram, *Leonardo* proposes another solution to resolve the question, which he posed to himself after the description of text T 4 and diagram M 3, i.e. How can the image arrive upright at the posterior surface of the crystalline lens in order to be seized there by the optic nerve?
Leonardo keeps the first crossing in the *sphera luce*, but modifies the passage of the rays in the crystalline lens. The second crossing, described as essential for converting the inverted image to an upright image, no longer occurs within the substance of the crystalline lens, but enters the posterior surface of the lens and the termination of the optic nerve, on which the rays arrive thus in the form of an upright image. This proposition is also illustrated in folios 8 recto and 10 verso.
According to this second proposal, the crystalline lens would not play any role in transmission for the second crossing of rays situated between the lens-albugineous interface and the optic nerve head.

This diagram is reversed in contrast to other diagrams in this folio: the entrance of rays occurs here from above. The uveal sphere (crystalline lens and vitreous) occupies almost the whole of the posterior chamber. This diagram is evocative of those of the *Perspectiva* of *Bacon*, where the rays traverse the ocular media, notably the uveal sphere, without crossing. For *Bacon*

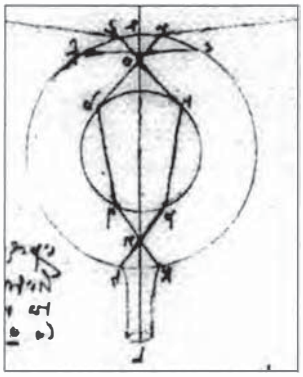


Figure 1 - 8

Leonardo da Vinci, Manuscript D, folio 3 verso (T 5).

This artificial eye drawing is placed in the center of the folio, and illustrates the second proposal of Leonardo to explain the intraocular conversion of inverted images to upright. This conversion to upright is made by two intraocular inversions of the rays: the first occurs in the sphera luce (already described in the previous drawing) and the second between the posterior surface of the crystalline lens and the optic nerve head. In this hypothesis, the crystalline lens would no longer capture the species, but would transmit them after a second crossing at the optic nerve head. This diagram is reversed with reference to others in this folio: the rays enter the eye from the top.

and his successors, the crystalline lens would only play a focusing role for the refraction of rays on to the optic nerve head. *Leonardo* adds two other crossings to this classical hypothesis of his own era: at first the pupillary crossing in accordance with the camera obscura, the second to make the image upright and not back to front so it is right way up and not reversed, in front of the optic nerve head.

Text (T 6) *(in margin of the schematic eye T 5, from 13.5 cm to 15 cm)*

"The experiment (12) shows that .p q. is one third of .t v."

"La speriçtia da che p q e sub 3 l0 al t v"

It is likely that *Leonardo* alludes here to the laws of refraction in liquids. As the vitreous humor is denser than the albugineous humor, the refraction would reduce the size of the images by a third. At the time of the era preceding the writing of Manuscript D, *Leonardo* was particularly interested in the dioptrics of refraction in liquids and lenses, as well as the catadioptrics of reflections in spherical mirrors and in their effects relating to magnification or minification.

Text (T 7) *(in margin of schematic eye diagram T 5 from 15 cm to 16,5 cm)*

"And because .p q. receives what is given to it by .t v., the more .t v. is restricted in its angle, the more .o. goes down."

"E þche p q riceue quel che li e dato dal .t v. tanto quãto .t v. si ristigne l ãgolo o piu òsscede »

Here *Leonardo* refers to the theory that the crystalline lens or its surface, the *rete aranea*, would detect the image on the cornea (.t v.) in proportion to the size of the pupillary aperture. In other passages, in particular in folios 5 verso, 6 verso and 7 recto, he also envisaged that the size of the perceived objects could be modified by the pupillary motility.

Sub-title (T 8) *(from 16.5 cm to 17.5 cm)*

"How the specie give themselves to the visual virtue with two compulsory cross-overs."

"Come le spetie si dãno alla uirtu visiua con due intersegationiÞ necessita"

The sub-title of the second paragraph of this folio announces the solution of the conversion of the image from being an inverted image to an upright image by a double intraocular crossing of the species, before their seizure by the optic nerve head, in order to cause their transformation into visual virtue.

Text (T 9) *(from 17.5 cm to 22 cm)*

"The object .a. sends its similitude (13) to the visual virtue by the line .a r. to the part .r. of the luce of the eye .c d f., then enters by the pupil .o. and makes the intersection at .o. and

12. "experience", this expression should not be interpreted in its modern restrictive sense. It has been used currently since Grosseteste and Bacon to designate conceptions picked up from day to day, observations made by third persons or written up in treatises and from divinely-inspired spiritual experiences. (Lindberg, 1996). See note 17.
13. "similitudne", literally 'similitude', often translated as 'resemblance'.
14. spera vitrea", the innermost sphere of the eye enclosing the vitreous and the crystalline lens.

passes to the vitreous sphere (14) in .v., and penetrates this sphere with the part .v q. and pass by the intersection (15) .n. and terminate in .k. in front of the optic nerve head .k h l., from which then it is transmitted to the common sense. Here the adversary says that the intersection .n. does not occur but that the same things is accomplished by the optic nerve and that the pyramid .n. is cut in front of the optic nerve, where small objects are made large."

"L obbietto..a. mãda la sua simjlitudne alla virtu visiva Þ la Þ linja. a r. alla parte. R. della luce .c d f. poi entra Þ la popilla .o. e ffa la intersegatione in .o. e passa alla spera vitrea in. v. e penetra essa spera colla parte .v q. e passa Þ la intesegatione .n. e ttermjna in .k. nella fronte del nervo ottitio .k h l. dal quale poi si referissce al sçso comune ðce qui l auersario che lla intersetione .n. nõ si fa ma sserve quella de neruj ottitj e che la piramjde .n. si taglia nella frõte del neruo ottirio dove le cose pichole si fanno rand"

This text comments on the hypothesis of the progress of the rays revealed in sketch T 5. Coming from the object "a", the *similitudes* strike the *luce* at "r", from where the refraction of the *spera luce,* across the pupil "o", directs them towards the point "v" on the anterior surface of the crystalline lens. The ray traverses the sphere of the crystalline lens, to emerge at "q".

Between the posterior surface of the crystalline lens and the optic nerve head, there would be a crossing of which "n" would be the center, after which the image would project on "k" on the optic papilla at "k" in order to transform itself into *visual virtue.*

The use of an *adversary* in a literary discourse was a current practice in the time of *Leonardo.* This adversary would present the theory held by *Bacon* in the *Perspectiva* that the rays of light, when leaving the posterior surface of the crystalline lens would simply focus on the optic nerve head without undergoing any crossing.

Two schematic Eye Diagrams (M 5)
(in margin from 16.5 cm to 20 cm)
(Figure 1-9)

These two drawings traced with geometric dividers and having a central axis, take up again the principle of the intra-crystalline lens crossing of the artificial eye M 1 and the schematic eye M 3. They have in common, on the other hand, the unusual feature of possessing in common a abnormally large vitreous sphere, with reference to other diagrams of Manuscript D.

On one of the diagrams, a *spera della luce* is added and this is concentric with the pupillary aperture. The *sphera luce* is

15. "intersegatione", 'crossing' according to Corbeau (1964).

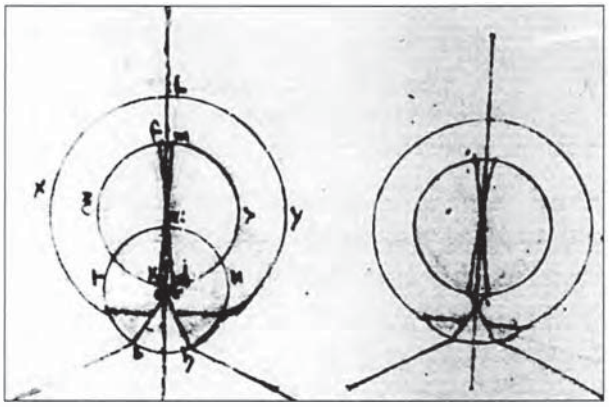


Figure 1 - 9

Leonardo da Vinci, Manuscript D, folio 3 verso (M 5).

The two sketches of schematic eye are placed in the lower margin of this folio. According to this proposal, a crossing of rays inside the crystalline lens makes the conversion of the inverted image to an upright. Leonardo illustrates once again his first proposal.

The sketches are traced with geometric dividers and relate to a central axis. The crystalline lens is abnormally extended. The right-hand diagram presents a spera dell luce centered on the pupil, well produced by the dividers.

for *Leonardo da Vinci* the site of the first crossing of light rays and of the first inverted image.

The text M 6 in the margin of these two diagrams has been visibly added later.

Text (M 6) *(underneath the two schematic eye diagrams in margin from 20 cm to 22 cm)*

"The vitreous sphere is placed in the middle of the eye in order to reinvert the species which intersect inside the small hole of the pupil, in order that the right returns to the right and the left returns to the left by means of the second intersection that occurs at the center of such a vitreous sphere."

"La spera ujtrea e messa nel mezo dell ochio Þ ðrizare le spetie che ss intersegano dentro allo sspiracolo detto popilla accoche lla desstra ritornj destra e lla sinisstra ritornj sinjstra nella itersegation secòda che ssi fa nel centro d essa spera vitrea"

This text forms the legend of the two diagrams M 5. Here *Leonardo* returns to his first theme enunciated in T 4 and illustrated by the schematic artificial eye M 1 and the diagram M 3. It comes back to the role of the vitreous sphere (here disproportionately enlarged in order to show its importance) in a hypothetical second intraocular crossing in regard to the conversion of the inverted image to upright before its detection as an upright image by the optic nerve, the first crossing being that at the pupil, according to the principle of the camera obscura.

1.1.2 – Folio 7 verso of Manuscript D

A - The Structure of Folio 7 verso

(Figures 1 - 10 & 1 - 11)

Folio 7 verso of Manuscript D reveals the *uveal theory* of the catadioptric inversion of the intraocular image. The folio carries the general title "*dell occhio*" (*On the eye*). It is divided into two parts in a vertical direction:
The first, **principal part** that occupies two thirds of the width is formed from a homogeneous text sub-titled:

"*Why an object on the right does not appear on the left inside the eye*".

"*Perche la cosa desstra no pare sinjstra nell ochio*"

The second, **in the margin** of the previous part, includes several diagrams surrounded by texts. From above down, these are:

- Two schematic diagrams of the eye;
- Three immersion cups;
- A text with pictographs of spheres and cupolas.

B - The Sequences of Folio 7 verso

For my analysis, I am going to divide folio 7 verso into localized sequences as follows:

1. according to their position expressed in centimeters with reference to the upper border of the folio (the total height of the folio is 22 cm),
2. in respect of their localization:
   - A *textual part* (sequences T 1 to T 6),
   - A *marginal part* (sequences M 1 to M 7).

Thus, the elements will be numbered from above down and identified according to whether they are placed in the principal text (T) or in the marginal text (M).

I will describe the text as follows:

1. The **general title** and the **sub-title** (from 1 to 2 cm) **T 1**
2. The **principal homogeneous text** (from 2 to 22 cm), which I am artificially dividing into five parts:
   - Part one (from 2 to 6.50 cm) **T 2**
   - Part two (from 6.50 to 10.50 cm) **T 3**
   - Part three (from 10,50 to 12.50 cm) **T 4**
   - Part four (from 12.50 to 16 cm) **T 5**
   - Part five (from 16 to 22 cm) **T 6**
3. The **marginal text** from above down:
   - An artificial eye diagram (from 2 to 5 cm) **M 1**
   - A text of ten lines surrounding an artificial eye (from 5 to 9 cm) **M 2**
   - A second artificial eye diagram and a text (from 5 to 11 cm) **M 2 & M 3**
   - A text of four lines underneath the artificial eye diagram **M 3**

Figure 1 - 10

Leonardo da Vinci, Manuscript D, folio 7 verso.
(original dimensions: 220 x 180 mm)

Here we find, once again, the mirror writing typical of Leonardo's papers. The pagination, in normal writing from left to right, is indicated only on the recto folios. The reader needs to reverse the mirror writing. The text contains no periods or commas to delimit and separate the sentences.

For this analysis, the document is catalogued in two parts:

- on the left, a main section (the sequences of texts T 1 to T 6) with a title and a sub-title,
- on the right, a margin (the sequences M 1 to M 7) comprising two drawings of artificial eye with their legends, three immersion cups, and a text with pictograms.

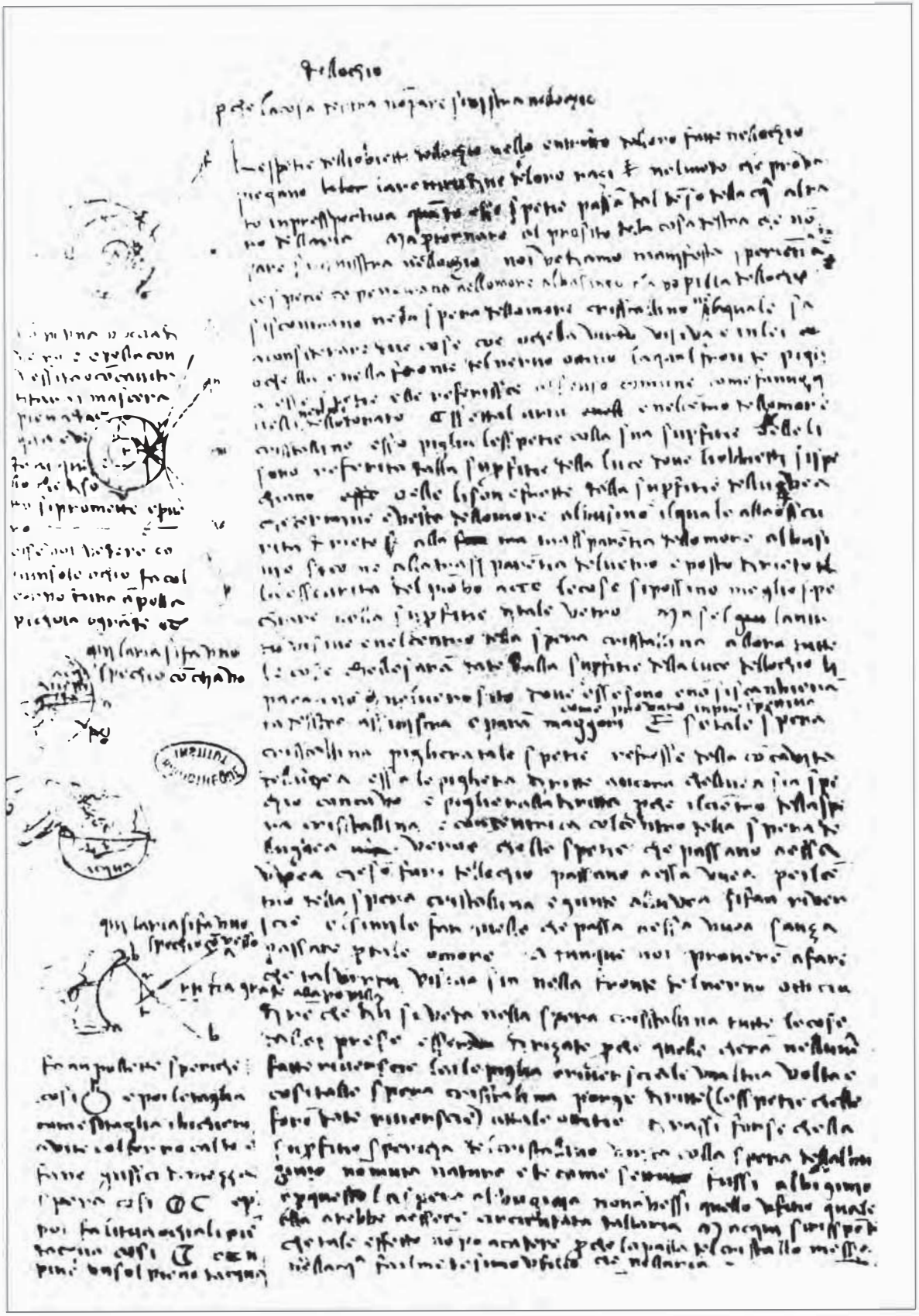


Figure 1 - 11

Leonardo da Vinci, Manuscript D, folio 7 verso.

The mirror writing is reversed (to read from left to right) in order to facilitate deciphering of the text.

- A diagram of a concave cup in front of an eye and texts (from 11 to 13 cm) **M 4**
- A diagram of a head in a cup filled with water (from 13 to 15 cm) **M 5**
- A diagram of a convex cup in front of an eye and texts (from 15 to 18 cm) **M 6**
- A nine-line text, with pictographs (from 18 to 22 cm) **M 7**

Title and Sub-title (T 1) *(between the high margin and 2 cm)*

"On the eye"

"Dell ochio"

"Why an object on the right does not appear on the left inside the eye."

"Perche la cosa dessтra nò pare sinjstra nell ochio"

Folio 7 verso is therefore dedicated, like folio 3 verso, to the conversion of inverted images to upright images inside the eye. The eye is likened to a camera obscura, in which images are projected as inverted images, whereas we see them as upright images. *Leonardo* produces several hypotheses in order to explain how this conversion of inverted images to upright images occurs.

The title *"dell ochio"* is found also at the head of folios 1 recto, 1 verso, 2 recto, 7 recto, 10 recto and 10 verso. This caused *Corbeau* (1964) to declare that their production had to have occurred at around the same time period. These folios are also dedicated to the direction of travel of rays in the interior of spherical surfaces (cornea, curved mirrors, etc).

First Part of the Text (T 2) *(from 2 cm to 6.5 cm)*

"The species from objects as they enter the eye undergo bending of the straightness of their rays in the proven fashion which is observed in perspective, as when these species pass from the density of water to the rareness of air (16). But to come back to the proposition that an object on the right does not appear on the left inside the eye, we see clearly by manifest experience (17) that the species which penetrate through the pupil of the eye into the albugineous humor, meet each other (18) in the sphere of the crystalline humor, in which it is necessary to consider two things i.e. either the visual virtue resides in it, or this is in front of the optic nerve, and this nerve seizes the species and transmits them to the common sensorium, in a fashion similar to how the olfactory nerves function."

"Le specie delli obietti dell ochio nello entroito da lloro fatte nell ochio piegano la rettituòne de i loro razi nel modo ch e provato in presspectiua quãdo esse spetie passã dal dçso dell acq al raro dell aria Ma Þr tornare al prosito della cosa destra che nò pare sinjnisstra nell ochio noi veòamo manjfesta speriçtia le spetie ce penetrana nell omore albusineo Þ la popilla dell ochio si scontrano nella spera dell omore crisstallino ne quale s a considerare due core coe o che lla virtu visiva e in lei o ch ella e nella fronte del neruo ottitio la qual fronte piglija esse spetie e lle referissce al senso comune come fanno quelli nerui dell odorato"

16. "The particles pass from the density of water to the rareness ("al rare") of air": It is possible that Leonardo was thinking of the extramission theory, and probably meant that the particles passed from the rarity of air to the denseness of water.
17. "by manifest experience", this expression was used at the time to indicate ideas gained from everyday life, from the observations of third persons, classical authorities and also the divinely-inspired spiritual experience. (See note 12)
18. "fall in or meet with each other", 'cross'.

Leonardo explains, by way of introduction, that the rays coming from objects situated in space bend and come together as they pass from air towards the cornea. In the pupil, the rays cross and invert according to the principle of the camera obscura. We still have to explain why we perceive images as upright and not inverted.

Leonardo recalls two hypotheses in regard to the perception of images: the classical one of perception by the crystalline lens (*"where the visual virtue is inside it")* and that of perception by the optic nerve head *("in the front of the optic nerve").*

In the *Galenic* tradition, the crystalline lens was considered to be the seat of the visual power of the eye. Nevertheless, *Leonardo* was attracted by the hypothesis of perception by the optic nerve head (see also folios 3 recto and verso). That idea seemed plausible to him following the example of the olfactory nerve. This is a remarkable comparison and reveals a sense of *Cartesian* reasoning before its time. In all cases, *Leonardo* had to determine the position of a second crossing of light rays inside the eye, which would rectify the inverted image because he did not know that, in fact, the images remained inverted and were not converted to upright images inside the eye.

Second Part of the Text (T 3) *(from 5 cm to 10 cm)*

*"And if this virtue is in the center of the crystalline humor it catches the species with its surface and these are transmitted by the surface of the luce (19) where the objects are reflected as in a mirror (*20) *or, alternatively, they are reflected from the surface of the uvea which is the termination and the covering of the albugineous humor, where there is an opacity behind the transparency of the albugineous humor, just as a pane of glass has lead placed behind it for opacification, so that objects may be better reflected in the surface of this glass."*

"E sse ttal urtu e nel cçtro dell omore crisstallino esso piglia le sspetie colla sua suÞfitie s e elle li sono referite dalla suÞfitie della luce doue li obbietti si spechiano o elle li son efrette dalla suÞfitie dell uvea ch e termjne e vesta dell omore albusino il quale a lla osscuritaðrietro alla trassperçtia dell omore albusinjo si como alla trassparçtia del uetro e posto òrieto la osscurita del piôbo acco le cose si possino meglio spechiare nella suÞfitie òtale vetro"

Here *Leonardo* describes at first the classical theory that the images of objects are reflected on the *luce*. These images would be detected there by the crystalline lens surface, so that they could be transmitted to the common sensorium, such as he also described in folio 3 verso.

Then *Leonardo* presents a new alternative mechanism for converting inverted images to upright images within the eye. He announces the *"uveal theory"*, according to which the uvea would act as a mirror, reflecting the images in order to change these from inverted images to upright images, which is the basic theme expressed in folio 7 verso. *Leonardo* tries to transpose the rules of catadioptrics to the eye (21). According to these rules, the crystalline lens would receive upright images, which had been converted from inverted to upright images by their reflection at the concavity of the uveal mirror.

19. "luce" and "luce dell ochio", translated by Corbeau (1964) as 'receptive surface of the light' or 'part of the eye reflecting the light', by Strong (1967) as 'cornea'. I prefer to keep the term 'luce', the various meanings of which I will explain later.
20. "spechiano", 'to be reflected', 'reflect', 'gleam' or 'glisten'.
21. Catadioptrics: study of optical systems involving a mirror.

Third Part of the Text (T 4)
(from 10.5 cm to 12.5 cm)

"But if the visual virtue is in the center of the crystalline sphere, then in that case all the objects which will be given to it by the surface of the luce of the eye (22) will appear in their correct position in which they are and not be inverted or reversed from right to left or vice versa, and they will appear larger, as it was proven in perspective."

"Ma se la uirtu visiue e nel centro della spera crisstallina allora tutte le cose che lle sarà date dalla subrfitie della luce dell occhio lj paranno nel uero sito doue esse sono e nô si scanbierà da desstra a ssinjstra e parà maggori com e provato in prespettiua"

Leonardo explains why the classical theory of seizure of images by the crystalline lens was not acceptable, because the images would be viewed as inverted. Even in the case where its concave surface would produce a reflection in the interior of the crystalline lens, that situation would produce an image enlargement, in the same way as concave distorting mirrors.

Fourth Part of the Text (T 5)
(from 12.5 cm to 16 cm)
(Figure 1 – 12)

"And if this crystalline sphere seized these species reflected from the concavity of the uvea, it would seize them still upright, because the uvea is a concave mirror; and it would seize them thus [i.e. upright] because the center of the crystalline sphere is concentric with the center of the sphere of the uvea. It is true that the species which are outside of the eye and which pass by the uvea reach it via the center of the crystalline sphere, and, having arrived at the uvea, they are reversed, and the same thing happens to those species which pass to the uvea without passing through this humor."

22. See note 19.

A. Original *B. Reversed*

Figure 1 - 12

Leonardo da Vinci, Manuscript D, folio 7 verso. Upper part of the margin. Drawings of the eye M 1 and M 3, text M 2.

The two drawings of the eye illustrate the uveal theory. After their first crossing in the pupil of the luce, the rays are reflected by the surface of the uvea in order to hit the crystalline lens surface.

The upper drawing represents a sphere of the luce coinciding with the uveal sphere and a crystalline lens sphere centered on this latter. The rays are reflected by the choroid and rejoin the posterior surface of the crystalline lens, where the optic nerve "captures" the inverted images after conversion of these to upright by reflection in the uveal mirror.

The lower drawing shows that the rays issuing from two objects of different size give different projections at the surface of the crystalline lens after their reflexion in the uvea.

This drawing is surrounded by the following text:
"ropi vna boccia di vetro e e della convessita e cocauita ti farai mascere peina d acqua e devrai quello che di sotto es vera"
(Break a glass carafe and with its convexity and concavity make a water-filled mask and you will see that what is promised below is true).
This text introduces the water-masks drawings, showing how to perform an experiment to prove that a concave mirror reflects and inverts images, just as the uveal mirror reflects and inverts images in the eye, according to Leonardo's "uveal theory".

"E se tale spera crisstallina pigliera tale spetie refresse della cõcavita dell uvea essa le pigliera ðritte ancora che ll uea sia spechio concavo e pilieralla ðritta Þrche il ciçtro della spera cristalljna e concentrica col centro della spera dell ughea vero e che lle spetie che passano a essa vvea che sô fori dell ochio passano a essa vuea pe il cçtro della spera cristallina e gunte all uvea si fan riverscie e l simjle fan quelle che passã a essa vuea sanza passare per tale omore"

Leonardo proclaims his *uveal theory* as follows: the rays entering the eye would be sent directly to the uvea, where they would be turned upside-down and then placed the right way up on their return to the crystalline lens, in order to be perceived the right way up there. The uvea would act like a concave mirror: its somber color being likened to the coating of the mirror. The role of the crystalline lens would be to perceive this reflected image. Finally, *Leonardo* rejects this theory also. The text is illustrated by figures M 1 and M 3 in the margin.

In the second sentence, *Leonardo* brings out a variation of the *uveal theory*: the rays, after their entry into the eye, would pass first via the crystalline lens and then would be thrown back towards the uvea, whence they would return the right way up because of the mirror effect of the uvea.

Fifth Part of the Text (T 6) *(from 16 cm to 22 cm)*

"Therefore, we will show the proof that the visual virtue is in the front of the optic nerve. We will say that from there you can see rectified in the crystalline lens all those objects which were straightened by the lens, in the upright position, because they were turned upside down in the uvea. The uvea seizes them and turns them around one more time, just as the crystalline lens donates the particles, which have been converted to upright and which were presented to it upside down, to the optic nerve. You will say perhaps that the spherical surface of the crystalline lens, united with the albugineous sphere, does not change its nature and is as if everything was albugineous and for that reason the albugineous sphere would not have the role that it would have had were it surrounded by air. But at this point, one can reply that this effect cannot occur because the ball of crystal placed in water acts in the same way as it does in the air."

"Adunque noi proverç a fare che tal virtu visiua sia nella fronte del neruo ottitio ðre che Þ li si veda nella spera crisstallina tutte le cose da llej prese esser ðrizate Þerche quelle ch erã nell uue fatte riuerscie lei le piglia e riuersciale vn altra volta e cosi talle spera crisstallina porge ðritte - le sspetie che lle forô date riuerscie - a ttale ottitio ðrassi forse che lla suÞrfitie spericha del cristallino vnjta colla spera dell albuginjo nô muta natura ed e come se tutto fussi albuginjo e Þ questo la spera albuginja non avessi quello vfitio quale ella arebbe a essere circumdata dall aria Ma cquj si risspôde che tale effetto nô po acadere Þche la palla del cristallo messa nell acq fa il medesimo vfitio che nell aria"

It is a question of a new proposal of rectification of images, of which the meaning is obscure and has given rise to different interpretations.
Leonardo gives notice that he will bring proof that perception of the image occurs in the optic nerve head and not, as was believed in his time, in the crystalline lens. Certainly, the crystalline lens would receive images converted to upright images after inversion by the uveal mirror, but these images would be uniquely projected and not perceived. It is the optic nerve that would see these images in the crystalline lens, and the optic nerve would capture them and send them to the common sense.
By this interpretation, the crystalline lens would be uniquely an optical device. The rays, which penetrate the interior of the eye via the pupil would cross each other in the uveal sphere, and would be reflected in the crystalline lens, whence they would be refracted towards the optic nerve head. Thus, it is definitely the optic nerve head, which would

capture those images reflected by the uvea to the crystalline lens, according to the *uveal theory*. After having been converted to upright by the crystalline lens, they would be sent as upright images to the optic nerve. In folio 10 recto, *Leonardo* also rejects the hypothesis of a reflection of images by the uvea.

Leonardo does research to prove his theories by means of experiments with curved or spherical instruments, made of solid glass or filled with water, as are described in the margin. There is no doubt that he considered the eye as an optical instrument reproducible by experiment.

Diagram of an artificial Eye (M 1) *(above the margin, from 2 to 5 cm)*

On this schematic eye diagram, the light rays cross in the pupillary aperture, then, after their reflection at the uveal surface, they are perceived by the crystalline lens.

In this diagram, the sphere of the *luce* is abnormally large and the crystalline lens is centered on this sphere. The diagram has also the unusual feature of a very prominent optic nerve illustrating the importance, which *Leonardo* attributes to it. *(Figure 1 - 12)*

Text (M 2) *(10 lines around the diagram M 1, from 5 cm to 9 cm)*
(Figure 1 – 12)

"Break a glass carafe and with its convexity and concavity make a water-filled mask and you will see that what is promised below is true"

"Rôpi vna boccia ò vetro e e della convessita e côcauita ti farai mascera peina d acqua e vedrai quello che ò sotto si promette es uero"

The text clearly has no connection with the artificial eye diagrams M 1 and M 3, which it surrounds. This leads us to suppose that *Leonardo* has added it later and that it is thus the product of later reflections. It is followed by other texts and by the drawings of the series of *"masks filled with water"* (M 3 and M 4) and of the *"ochiali"* (M 6) from the lower half of the folio margin. *(Figure 1 – 12)*

Schematic Eye Diagram (M 3) *(from 5 cm to 11 cm)*

This drawing refers to the preceding artificial eye diagram M 1, which it compliments. It depicts the rays issuing out of two objects of different size, which would give uveal reflections such that their localization at the crystalline lens surface would be distinct. This would render the uveal theory revealed in texts T 2 to T 6 more plausible. *(Figure 1 - 12)*

The diagram has only a little, if any, relationship to the texts that surround it. On this drawing the sphere of the *luce* is no longer represented and the crystalline lens is situated at its traditional central position.

Text of four Lines (M 4) *(under the artificial eye diagram, from 9 cm to 11 cm)*

"And if you want to see with only one eye, use the body of a small or large ampulla etc."

"E sse voi vedere con un solo ochio fa col corpo d una ãpolla pichola o grade eccetera"

This text has evidently no connection with the drawing, although, by virtue of its position,

it would seem to be the legend of it. It introduces the text M 7 at the bottom of the margin on ampoules and cupules. This makes to suppose that it was added after the other texts and diagrams.

Diagram of a concave Mirror in Front of an Eye and Texts (M 4)
(from 11 cm to 13 cm)
(Figure 1 - 13)

"Tepid water." (23)

"Acq tiepida"

"Here the air makes a concave mirror." (24)

"Quj l aria si fa vno spechio cóchavo"

This text on concave mirrors is placed in the margin of the diagram illustrating the *uveal theory.* A concave mirror there simulates the uvea and reflects rays towards its center. *Leonardo* placed the observer's eye at this strategic point, as he also did in the artificial eye diagram of folio 3 verso. The light rays would thus be reflected at the uveal surface (choroid) and would be focused in the crystalline lens. Curiously, *Leonardo* does not mention the mirror coating.

Diagram of a Head in a Cup filled with Water (M 5) *(from 13 to 15 cm)*
(Figure 1 – 13)

"Water" (25)

"Acqua"

This drawing suggests an experimental transposition of the principle of the concave cup shown above this at M 4. Here, the cup is in a horizontal position and is fixed by links.

This diagram has often been used to attribute the invention of the principle of contact lenses to *Leonardo da Vinci.* According to these authors, it would represent a giant contact lens, which would give improved visual acuity to the observer whose face is immersed in it. The context and the legends show, in any event, without ambiguity, that *Leonardo* was concerned with catadioptric experiments and not with ocular correction. Plunging the head into a spherical mirror has nothing to do with visual correction.

23. "acqu tiepida", text within the drawing. Luke-warm water is supposed to be less dense than cold water, for which reason you can see currents rising in water which is being heated.
24. The text is placed in the body of the drawing.
25. Text placed above the drawing

Diagram of a convex Mirror in Front of an Eye and Texts (M 6)
(from 15 cm to 18 cm)
(Figure 1 – 13)

"Here the air becomes a convex mirror." (26)

"Quj l aria si fa vno spechio côvesso"

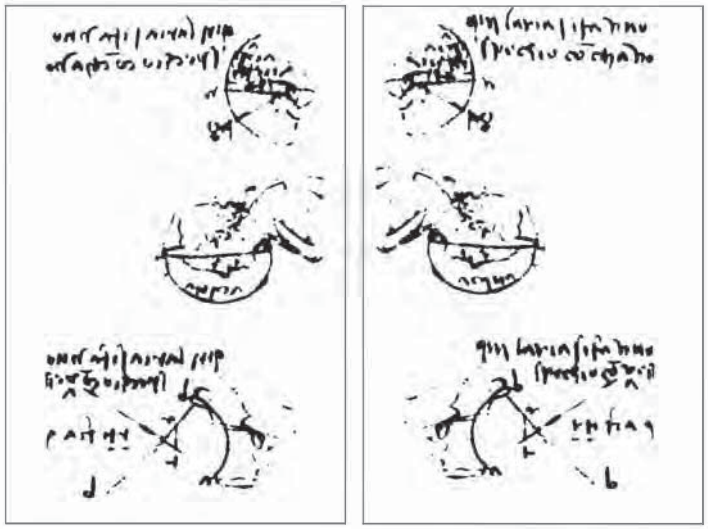
".r t. will become large like the pupil." (27)

".r t. fia grade alla popilla"

The interpretation of this drawing is not easy. There is no reference to a convex mirror in the texts of folio 7 verso or anywhere in Manuscript D.

For *Strong* (1967), the presence of a screen larger than the pupil and the reference to the pupil would demonstrate that this diagram takes up again or announces or revisits the experiment on vision across a stenopeic hole to which *Leonardo* devotes folios 6 verso and 9 recto of Manuscript D.

It seems logical to accept that *Leonardo* pursued his reflections on spherical mirrors, and that after expressing his views on concave mirrors, he was interested mainly in convex mirrors. This viewpoint depends on the similarity of the diagram M 4 to a concave mirror. In any event, it is a question of **catadioptric** experiments, of which the description will be found in the next chapter, with the eyes covered only with shells of smallest size.



A. Original *B. Reversed*

Figure 1 - 13

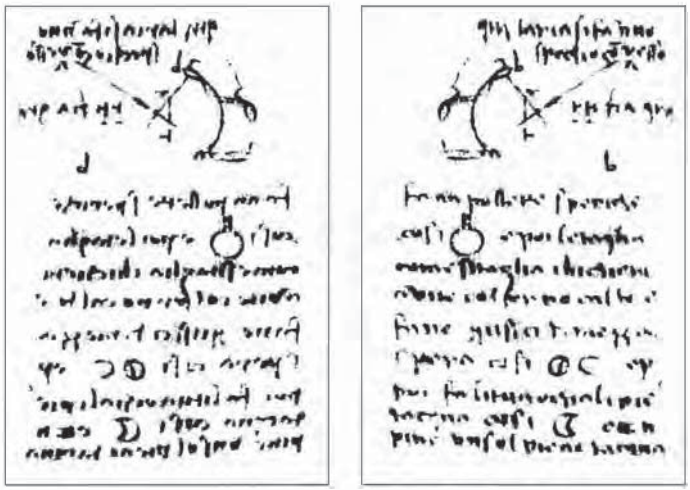
Leonardo da Vinci, Manuscript D, folio 7 verso.
Three drawings of mirrors placed in front of the eye or the face (M 4, M 5, M 6).

The drawings M 4 and M 5 represent concave mirrors, the diagram M 6 a convex mirror in front of the eye.
The adjacent texts indicate:
-1- the upper proposition: "quj l aria si fa vno spechio côchavo"
(Here the air makes a concave mirror) and "acqua terpida" (tepid warm water),
-2- the proposal for the medium: "acqua" (water)
-3- the lower proposal "quj l aria si fa vno specio côvesso" (Here the air makes a convex mirror) and "r.t. fia grande alla popilla" (r.t. will become large like the pupil).

The diagram M 5 proposes a catadioptric experiment in order to illustrate the uveal theory exposed on this folio. The cups represent concave mirrors, which reflect the rays towards the eye, in the same way as the uvea reflects the rays towards the crystalline lens.
The drawing M 6 with a convex mirror and the interposition of a screen as large as the pupil would indicate experiments across a stenopeic hole.

These sketches of curved mirrors have always been interpreted, but incorrectly, as experiments involving corneal neutralization by a liquid and have served as a basis for the myth that Leonardo da Vinci was the inventor of the contact lens. According to these authors, the mirrors represented giant concave and convex contact lenses, for the correction of ametropia.

26. Text placed in margin of the diagram
27. Placed at the edge in the space of text T 6



A. Original *B. Reversed*

Figure 1 - 14

Leonardo da Vinci, Manuscript D, folio 7 verso.
Text with pictograms (M 7).
(original dimension: 64 mm x 95 mm)

This text at the bottom of the margin of this folio is characterized by pictograms representing an ampoule and shells.

In this text, Leonardo proposes:

1. to make some *"ampolette spheriche"* (small spherical ampoules),
2. to cut them and make out of them some *"gussci de mezza spera"* (shells of half sphere),
3. then to make from them some *"occiali pie d'acqua"* (ochiali full of water),
4. or only to fill *"vn sole pieno d'acqua"* (only one full of water).

There is no doubt that Leonardo da Vinci is proposing to perform catadioptric experiments using curved mirrors, which would be easier to perform with glass shells than with the large facial cups as described above.

Certain authors have interpreted this text and its pictographs as being the description of contact lenses and contact shells. However, the context does not contain any argument, which would justify such an interpretation. Everything leads one to believe that Leonardo was proposing to carry out catadioptric experiments as described in the text of this folio, and there is no argument to support the correction of ametropia.

The use of the term *"occiali"* (eye cups, spectacles), in the proposal of these catadioptric experiments should not in itself be allowed to induce in error. At the beginning of the 16th century, spectacles were "nailed" spectacles", consisting of two mounted glass lenses, held together by a hinge (the nail), stuck on the nose at this point of contact.

Text with Pictographs (M 7)

(from 18 to 22 cm)

(Figure 1 - 14)

"Make small spherical ampoules like this – figurine – *and then cut them down just as "bicheri" (28) are cut with a hot iron, and make shells of half sphere, like this* – figurine – *and then make for thyself "ochiali" (29) full of water, like this* – figurine – *and fill only one full of water."*

"Fa ampollette speriche cosi – figure - *e poi le taglia come si taglia i bichieri a vite col ferro caldo e fane gussci ò mezza spera cosi* – figure - *e p poi fa li tua ochiali piç d acqua cosi* –figure - *e en pine vn sol pieno d acqua"*

Leonardo proposes to carry out the catadioptric experiments on concave mirrors, described above (M 4, M 5, M 6), by using little concave glass shells placed in front of the eye. He often uses pictographic conventions starting from around 1500.

Even if *Leonardo* has not intentionally and specifically envisaged neutralization of the corneal dioptric power by a liquid, it is a fact that he depicted in his drawings large and small concave devices that were filled with water and placed in front of the eyes. In no instance was this instrument destined to replace the neutralized cornea, but it was required to *"make a water filled mask" ("farai mascera peina d'acqua")* or *"make a mirror" ("fa uno spechio")*, as he promised above in M 2, M 3, M 4 and M 6.

28. "bicheri", drinking glasses, goblets. Corbeau translates "I bicherieri a vite" as 'drinking glasses'.
29. "ochiali", eyecups, small cups for bathing the eyes (shells for bathing the eyes), sometimes translated as 'eye glasses'.

1.1.3 - Folios 3 verso and 7 verso in the Context of Manuscript D

It would be difficult to assess appropriately the content of the two isolated folios of this manuscript without having placed them in the context of Leonardo's Manuscript D. The titles and sub-titles of the ten folios are reviewed in the appendix.

It should be remembered that, contrary to generally accepted ideas, Manuscript D is not a treatise divided into chapters or a review of previous endeavors. It includes erasures, recollections from memory and references to ideas for further development or provocative experiments.
Each of the pages of Manuscript D carries the titles *"dell occhio" (On the eye)* or *"occhio humano" (On human eye).* Even if ocular anatomical terms are numerous, Manuscript D is not a textbook of anatomy. The true subject matter lies in explanation, in the light of the current thinking of the era and by means of a series of schematic diagrams of the artificial eye, of the means of production of the image from the cornea up to the optic nerve. *Leonardo* thus makes his journey from anatomy and physiology towards physics. He even reduces the eye to a very simple geometric figure, without in any way leaving out comments on the relationships between objects of sight and perceived images or between eye and brain.

The themes revealed in Manuscript D are found elsewhere in other writings of *Leonardo*. Thus, we find drawings and texts, which are similar, especially in Manuscript K and the Codex atlanticus.

1.2 – Manuscript K from Institut de France

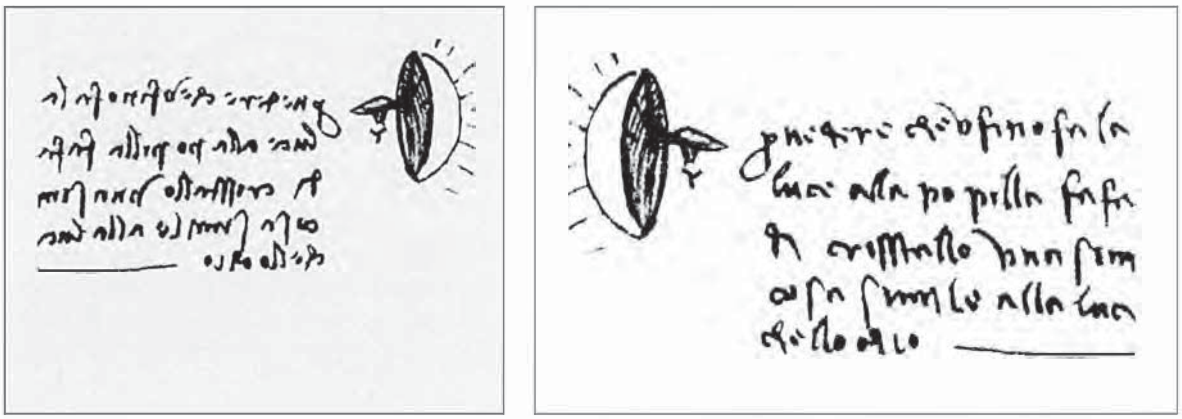
Various authors commonly attribute the drawing and the description of a *contact lens to* the diagram and text of folio 118 verso in Manuscript K. Certain historians would see in this passage the description of a method of fabrication of such a *glass cornea made from crystal*, and in the accompanying drawing the representation of a corneal immersion. However, not everyone agrees with this opinion (30).

Manuscript K, also preserved at the *Bibliothèque Mazarine* of the *Institut de France*, is presented in the form of a small-sized notebook (64 mm x 95 mm). It seems to have been used as a book for jottings, its content being quite varied. I have used the classical text, with facsimiles of the folios of *Ravaisson-Mollien* for this study.

1.2 1 – Folio 118 verso of Manuscript K

(Figure 1 - 15)

Folio 118 verso is presented as an empty folio, with the exception of its superior quarter, which contains a **text** of five lines on the left and a **diagram** on the right.



A. Original *B. Reversed*

Figure 1 - 15

Leonardo da Vinci, Manuscript K, folio 118 verso.
Diagram of a lens in front of an eye.

The diagram is accompanied by the following legend:

"To see what function the luce performs for the pupil, make out of crystal an object similar to the luce of the eye."

"per uedere chevfitio fa la Luce alla popilla fafare di cristallo vna cosa simile alla luce dellochio"

In the era of the drafting of Manuscript K, Leonardo attribute to the expression "luce dell ochio" (luce of the eye), the meaning of "the part of the eye which illuminates", therefore the corneal sphere, as was explained in folio 119 recto.

It is an object "made out of crystal", similar to the luce of the eye, which Leonardo proposes to place in front of the eye in order to focus the rays on the pupil and to explain the stretching of the visual field which permits visualization "behind the shoulders".

30. For listing and references to the authors supporting or rejecting this viewpoint, see Ehrich & Heitz

A - The Text

The text recommends that one should "*make out of crystal, an object similar to the luce of the eye*", which would be placed in front of the eye:

"To see what function the luce performs for the pupil, make out of crystal an object similar to the luce of the eye."

"*Per uedere cheyfitio fa la luce alla popilla fafare d cristallo vna cosa simile alla luce dellochio*"

B - The Diagram

The diagram represents a cupola or a lens, plano behind and convex in front, that illustrates the *crystal object*. Behind the plano surface of the lens and centered on it, an eye is drawn in lateral view. Eight rays are drawn in front of the convex surface.

C - The 'luce' of Crystal

According to the text, the *object of crystal* would be *"simile alla luce dellochio"* (*similar to the luce of the eye) Leonardo* attributes to the luce both the meaning of the pupil, the cornea and also the corneo-cameral complex of the eye (cornea and aqueous humor) (31). The strokes on the posterior surface of the *object of crystal* would lead one to suppose that it would be like a plano-convex lens, solid and that there is no question of its being an empty shell. *Leonardo* indicates that the *object* should be made from *crystal*. Thus, it would be fashioned from a block of quartz and not cut out of a glass bowl in the manner of eyecups and cupolas in the folios of Manuscript D. The crystal object is placed a short distance in front of the eye. The eye itself is placed opposite the center of the object's base, at the precise position where the pupillary aperture would be if the structure were the anterior segment of the eye. The rays, from in front of the convex surface, converge towards the center of the base, in a location facing the eye.

To confuse the diagram of this folio with a contact lens and to interpret the text as meaning that *Leonardo* recommended cutting a lens out of crystal like the *luce of the eye* does not conform to the truth. It is a question of a block of crystal, cut into the shape of a plano-convex lens, which is then placed in front of the eye. The plano-convex lens is centered on the observer's eye, where the rays of light converge from space and hit its anterior surface.

By this proposition, *Leonardo* wishes to demonstrate that the convexity of the cornea allows enlargement of the visual field. In any case he does not envisage the correction of a resultant visual deficiency. In order not to allow any persisting doubts regarding the significance that *Leonardo* gave to the '*luce dell occhio*', one should refer to the explanation of the pupil and of the *luce*, that he gives in the following folio, i.e. folio 119 recto.

1.2 2 – Folio 119 recto of Manuscript K

(Figure 1 – 16. A & B)

Folio 119 recto includes two texts and two diagrams.

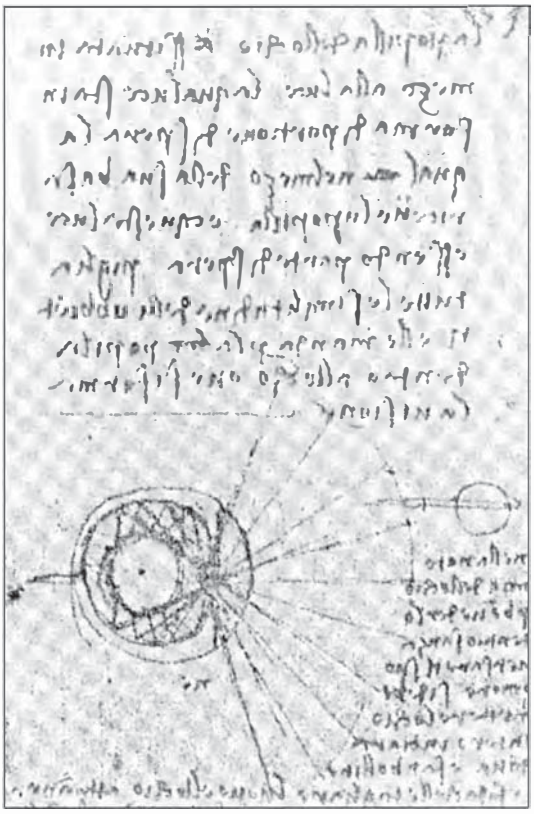


Figure 1 - 16.A

Leonardo da Vinci, Manuscript K, folio 119 recto. (Original dimension: 64 mm x 95 mm)

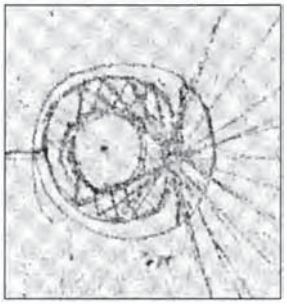


Figure 1 - 16.B

Leonardo da Vinci, Manuscript K, folio 119 recto, lower part.

Sketch illustrating the perception of the lateral visual field according to the uveal theory.

A - The 'luce' of Manuscript K

Leonardo explains in the first text that he means by "*luce*" a portion of the sphere of the eye having at its base the "*luce of the pupil*":

"The pupil of the eye is situated in the middle of the luce, that is in the form of a portion of a sphere which receives the pupil in the middle of its base. As this luce is part of a sphere, it takes all the similitudes of objects and dispatches them via the luce of the pupil inside the eye of the place where vision is produced."

"La popilla dellochio essituata in mezo alla luce laqua luce sta in forma di portione di spera la qual n nelmezo della sua basa riceue lapopilla ecquesta luce essendo parte di spera piblia tutte le similitudine delli obbjet ti elle manda perla luc pupilla dentro allocho oue siforma la visione"

The *luce* would therefore focus the *similitudes* on the pupil, where they would be turned around according to the principle of the camera obscura in order to reach the site of perception. There is therefore no longer any doubt that, in this passage, *Leonardo* means by *luce of the eye* the transparent part of the eye between the convexity of the anterior corneal surface in front and the pupillary plane behind, or in other words what we designate nowadays as the corneo-cameral complex.

Folio 119 recto also shows in its lower portion a diagram illustrating the *uveal theory*, in which the rays coming from space, the *similitudes*, are collected by the convexity of the *cornea-luce*, cross in the pupil *(luce of the pupil)*, are reflected by the choroid and finally hit the crystalline lens surface. *(Figure 16. B)*

Therefore, one can assert that the diagram of folio 118 verso, representing the "*object of crystal similar to the luce of the eye*" is a plano-convex lens made of crystal that is placed in front of the globe. This was intended to demonstrate that the convexity of the eye, notably the cornea including aqueous humor and anterior chamber, would allow the *similitudes* coming from the periphery of the visual field to focus on the pupil. According to the uveal theory, these *similitudes* would be projected on the albugineous sphere (the choroid), from which they would be reflected towards the surface of the crystalline lens.

B - The central Position of the Crystalline Lens

On the diagram of this folio, the **crystalline lens** is in the center of the globe, that is a location presumed indispensable for the collection of rays of *similitudes* reflected by the uvea. *Leonardo* attributed great importance to the central position of the crystalline lens. The text scribbled round the diagram explains in addition the method of preparing an eye to observe the topography of these components. The recommended procedure, of boiling, in any event liquefied the vitreous and broke the attachments of the crystalline lens, which structure, in turn, luxated towards the center of the globe. This procedure of preparation was current and explains the localization errors of the crystalline lens by the anatomists of this epoch.

1.3 - Folio 222 recto/a of Codex atlanticus

(Figure 1 – 17)

A sequence in f**olio 222 recto/a of the Codex atlanticus** of *Leonardo* is occasionally cited by contact lens historians for its allusion to the neutralization of the anterior dioptric power of both eyes and the replacement of the eliminated ocular diopter by a glass hemispherical structure placed in front of the figure.

These citations always refer to reproductions at second-hand or translations of general or popular works on *Leonardo* (32). As far as I know, no study of this text, placed in the context of the other passages in folio 222 recto/a, has been carried out up to the present time.

The Codex atlanticus of *Leonardo da Vinci* is preserved in the *Ambrosiana Library of Milan* (Italy). It is not readily accessible and is less known than that of other texts of *Leonardo*. To my knowledge, there is no available translation of it either into French or into English. For the present study, I have used a facsimile edited by the Ambrosiana Library and dating from the beginning of the last century. This edition includes deciphering and an approximate translation into Italian (33).

For this study, I propose to analyze the following two passages from folio 222 recto/a:

1. A passage and diagram at the **bottom** of the folio, where the *glass prefacial hemisphere* is described, that *Leonardo* uses to explain the perception of the peripheral visual field,
2. A text and two diagrams placed in the **upper part** of the folio, which describe visual perception in the periphery.

I will follow these analyses by a discussion and commentaries taking count of other similar passages in the work of *Leonardo*.
This folio does not contain any other allusion to an eventual neutralization of the ocular dioptric power or to the perception of lateral vision. The other passages of this folio are devoted to the description of several theories of conversion of the inverted image so that it is perceived to be upright, notwithstanding the likening of the eye to a camera obscura, according to which, the image should be projected as inverted inside the eye.

32. Essentially to the English translations of Argentieri (1956).
33. Leonardo da Vinci. "Il Codice Atlantico di Leonardo da Vinci nella Biblioteca Ambrosiana di Milano", Accademia dei Lincei, U. Hoepli, (8 vols.), 1894-1904.

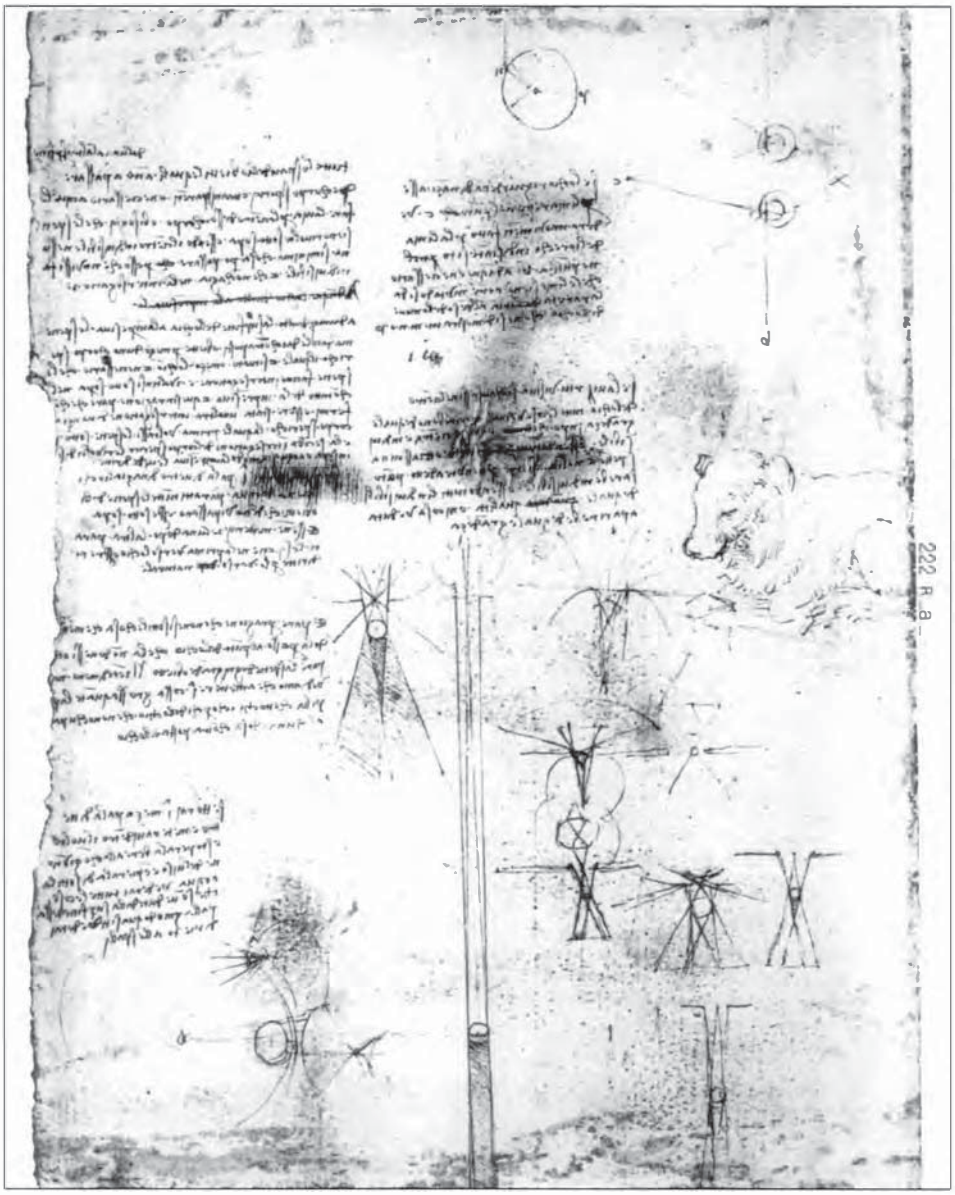


Figure 1 - 17

Leonardo da Vinci, Codex atlanticus, folio 222 recto/a.
Original non-reversed presentation

1.3.1 - The Glass Hemisphere of Folio 222 recto/a of Codex atlanticus

(Figure 1 - 18)

The text and diagram in connection with the glass hemisphere are placed in front of a human figure and are situated in the left inferior portion of the folio. Both text and diagram are partially superimposed on the sketch of a large circle traced by compass.

A - The Text

This text is relatively short and contains only seven and a half lines. Here it is with translation:

"If you takes a half of a glass bowl, if you immerses the head within the same (34) and you seal (35) it well at the junction with the face and you fill it with fine water, you will see all the things that are seen from the surface of this bowl, such that you may see in the direction of the shoulders."

"Setto raj l meza pala di uetro e mete rauj dêtro iluolto e stopera la bene alla chôvivtjo ne del ujso e êpierala di sottile acqua vederaj tutte le cose che sô ue dute dalla superfitie dessa palla jmodo quasi ti vederaj dirieto a lle spallj"

Leonardo is describing an experiment consisting of:

1. preparing a glass hemisphe-rical cup,
2. filling this hemisphere with water,
3. submerging the head inside the hemisphere and ensuring that the junction between head and hemisphere is watertight.

The recommended set-up should demonstrate that the glass cup would allow the experimenter to see up to "*the shoulders*". *Leonardo* emphasizes that it is the surface of the bowl ("*palla*"), or outer surface of the hemisphere, that actually allows the objects to be seen..

34. Deciphering of "il uolto" (il volto): 'the head'.
35. Verb "stopera" derived from "stuppa" (or "stupa"): 'the seal'. The seal is made out of fibrous material, either hemp or linen. The English verb would be 'caulking': meaning 'sealing something with caulk'.

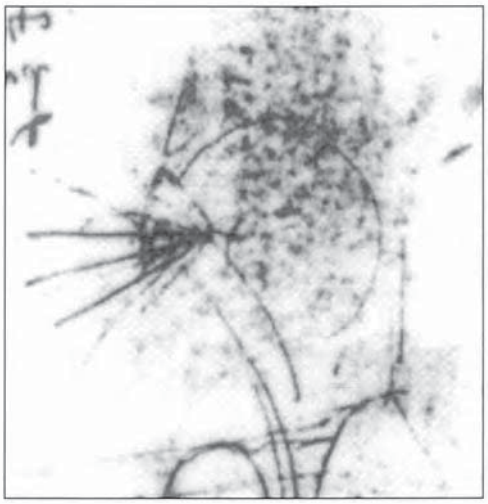


Figure 1 - 18

Leonardo da Vinci, Codex atlanticus, folio 222 recto/a.
Lateral lower part on folio 222 recto/a - enlargement.

The text of this folio proposes the immersion of the head in a hemisphere filled with water, the edge of which is watertight and to look across this hemisphere:

The aim of the experiment described by Leonardo would be to demonstrate that a structure with a convex anterior surface would enlarge the visual field. This acts like the convexity of the surface of the luce of the eye and would cause the rays from space, situated from as far back as behind the shoulders, to converge towards the pupil.

The proposed device neutralizes the corneal dioptric power through the water held in contact with the eye and replaces the neutralized surface by a new dioptric power consisting of the external surface of the glass hemisphere.
Several intricate circles are traced by means of dividers below the text. After enlargement, the upper circle shows the profile of a human face, on which the rays converge, centered on the circle. This would indicate that Leonardo was imagining a shell enclosing the face, and not a shell placed in front of the eye or the orbit.

The surface of the hemisphere forms a new refractive surface, as a substitute for the neutralized surface of the eyes. The proposed experiment, as described, consists of the neutralization by water of the face, therefore the eyes, and replacing the neutralized structures by a new refractive surface, comprising the outer surface of the glass hemisphere.

B - The Drawing

The diagram, that is immediately adjacent to the text, illustrates the hemisphere experiment. It depicts a circle traced by compass. A dozen straight lines undoubtedly show rays converging towards the lateral border of the circle. When they penetrate this, they break up and come together again to focus in the center of the sphere.

With a minute and detailed examination of the diagram, it is possible to recognize the outline of the lateral view of a human head, the figure of which is surrounded by the hemisphere. The hemisphere would touch the forehead and chin. After their break-up at the surface of the hemisphere, the rays converge in the direction of the eye.

This diagram, the originality of which has never been previously emphasized, illustrates the adjacent text, because, (a) the figure is located within the hemispheric cup and (b) the rays focus approximately on the eye.
Note also, that the light rays are refracted when they penetrate the cup "*as they pass from the thin air to the dense*" to the water of the cup, as is explained in a text above in the same folio, devoted to the perception of movements in the lateral visual field. This is the subject of the following analysis.

1.3.2 - The Text and the Diagrams of the upper Part of the Folio

(Figure 1 - 19)

This passage, complimentary to the one before, is located in the upper part of the folio. It is under a diagram illustrating a spherical structure and is juxtaposed to another diagram of two spheres with linear expansions.

Figure 1 - 19

Leonardo da Vinci, Codex Atlanticus, folio 222 recto/a - right upper part.

The first diagram, the spherical one, above the text, represents a globe of the eye. The point "o" corresponds to the impact of a lateral "visual ray". After its refraction at the surface of the globe, the line rejoins the center of the globe, then the bottom of the eye "p".

The second diagram, in the margin of the text, shows the stretching of the binocular visual field. This extends laterally from "a" to "b". At the center "c", the rays coming from each eye rejoin. The progress of the rays inside the two eyes is different, giving evidence of the uncertainties of Leonardo.

A - The Text

"If the eye looks in front of itself into the distance via a straight line towards a point c. it will see the movements made in passing by the line of the ears in a location situated in distance and passing by the points .a. and .b.; therefore it must be necessary that the lines break as they pass from the thinness of air to the density of the humor of the eye, as was shown in m.n.o.p."

"Se lochio riguardera di nàzi. assel perlinja rette nelputo (ch) c. vedera. imoviméti fatto per la linja de liorechi indistate sito (j nel) ne puti. a. b. aduque e ne ciessario che le linje sieno rette mvtado si da la rareta dellaria aldeso dollomore dellochio. chome si dimostra in .m. n. o. p."

This passage could signify that *Leonardo*:

- Observed the extent of the temporal visual field, in that the movements are visualized as far as the meridian passing by the ears.
- Concludes from this observation that the *lines* coming out of space inside of the central line *break* and are refracted at their entrance into the eye.
- Deduces therefrom that refraction of the *lines* results when the light rays *pass from the thinness of air to the density of the humor of the eye.*

B - The Drawing

Two neighboring diagrams illustrate the passage, as follows:

1. The first diagram that is situated above the text represents a circular structure, probably an ocular globe. It carries the notations *"n, o, p"*. The point *"n"* corresponds with the impact of a line representing the ray coming out of lateral visual space. The point *"o"* is in the center of the globe, while the point *"p" is* at its posterior pole, where, according to *Leonardo*, the passage of the "*similitudes*" towards the "*impressiva*" would be situated.

2. The second diagram, in the margin of the text, depicts two ocular globes, each containing in its center a circular structure indicating the crystalline lens. Rays are falling on these globes; some of these come from a central point *"c"* and others from a more peripheral area of the visual field as far as one line designated *"a. b"* that is perpendicular to the axis of the globes. A line representing the paths of the optic nerves and optic chiasma stretches out from the posterior part of each of the ocular spheres.

1.3.3 - The Chronology of the two Segments of Folio 222 recto/a of Codex atlanticus

The text and the diagrams of the bottom of folio 222 recto/a of the Codex atlanticus are very probably from an later edition than the other texts and diagrams of this folio. I am basing this hypothesis on the following two arguments:

1. The resemblance of the theme of *"vision behind the shoulders"* across from the glass hemisphere of the last paragraph that was referred to in *Leonardo's* last paragraph to that described in the first paragraph of the right column regarding the *vision behind the ears,* and

2. The superimposition of the text and the diagram at the bottom of the page on top of a schematic diagram of large size, representing a circle with adjacent conical formation like a child's spinning top.

These two arguments lead us to suppose that it would only be after rereading the folio that *Leonardo* would have added, in the partially free lower margin remaining, a text and a diagram inspired from the theme of vision behind the shoulders described in the first paragraph at the top of the page.

2. Discussion

2.1 - The Writings of Leonardo da Vinci in the Context of the Knowledge of his Era

The analysis of ancient texts demands that these are interpreted within the context of knowledge available at the time of their publication. The object of the present work is not however to describe the knowledge of optics and of the eye at the Renaissance. Consequently, I shall limit myself to a short introduction and refer the interested reader to specialized works such as *Strong* (1967), *Koelbing* (1967, 1987), *Lindberg* (1976,1996, 1997), *Grmek et al.* (1993, 1996), *Russell* (1997) and *Rashed et al.* (1997) (36).

2.1.1 – Ocular Anatomy and Physiology at the Time of the Renaissance

A - The Greek and Arabian Heritage

The Christian West has only a few works on optics that predate the first Greek and Arab translations of the 11th century. The most important Greek sources for the Arabian theoreticians on optics were *Plato, Euclid, Aristotle, Proclus, Ptolemy, Galen, Epicurus* and *Zeno*, with particular emphasis on *Galen, Aristotle* and *Ptolemy*. The Arabian world had dedicated a certain support for optics to the degree that it supported astrology and astronomy and to a less extent medicine. With the exception of *Alhazen*, the Arabian authors (*Humain, Al-Kindi, Avicenna, Averroes*) were generally more translators and compilers of literature than innovators. The attention of *Alhazen* to the emergence of physiological optics and the complex problem of the rupture with the antique optical world falls within the scope of this work. *Russell* has recently contributed an important analysis of this aspect (37). The Christian West has collected, progressively, Latin translations of scientific Greek treaties in the course of the 12th and 13th centuries, along with their Arabian commentaries and treaties, not to mention the diversities of their schools with all their polemics. This was followed by periods of uncertainty, and we can find traces of this, three centuries later in the works of *Leonardo da Vinci.*

B - The 'Perspectiva', a New Science

Robert Grosseteste was among the first to have revealed the science of optics to the Western world (38). He was Bishop of Oxford, and, according to *Lindberg,* he would only have had Latin translations of *Euclid (De Speculis), Avicenna (Liber canonis)* and *Aristotle* available to him (39). However to him goes the credit of having understood, contrary to his mentors, that optical questions can be treated by mathematical and, above all, by geometric rules.

36. Certain popular treatises on Leonardo are to be read with reservations: their citations are often second-hand, truncated and taken out of context of the work and of the knowledge available to that era. Some writers sound a paean of praise for Leonardo, whom they present to the world as both prophetic scientist and genius.
37. Russel in Rashed 1997, p. 319-354.
38. Grosseteste Robert (1175-1253).
39. Lindberg has recently published an exhaustive study on the Perspectiva: "Roger Bacon and the origin of Perspectiva in the Middle Ages" (Lindberg, 1996).

This reasoning allowed him to develop a new science that came to be called the *Perspectiva,* and this encompassed all available knowledge in connection with light, vision, and the eye.

A century later, *Roger Bacon* and *John Peckham* (40) had Latin translations of the Arabian treatises of *Al-Kindi* and particularly of *Alhazen (De aspectibus)* available and this allowed them to complete *Grosseteste's* work. *Bacon* edited the first Western European optical treatise, the *Perspectiva*, which formed Part V of his *Opus Major*. *Lindberg* furnished a translation of it accompanied by a pertinent discussion. For this author, the *Perspectiva* comprises the first Western European treatise containing geometric drawings, that support arguments to clarify the theory of vision, the pathway of light including reflection and refraction, image reversal in mirrors and so on. *Bacon* modernized optics using precise mathematical and geometric explanations as a basis for his inspiration.

The *Perspectiva* thus became a new science devoted to the study not only of light, but also of vision and the eye:

- The rectilinear propagation of light rays became apparent, and reflections and refractions were only accidental.
- The study of vision included also that of perspective as described.
- The eye itself is a geometric entity, but it remains largely linked to Galenic traditions.

The *Perspectiva* remained initially an academic science that was not connected with the practice of medicine or surgery. It was the subject of discussions, debates, and polemics in the academic field that were based on quotations from classical authors. It was only in the course of the following centuries that the *Perspectiva* became more practical, more mechanistic and more experimental. This was due to the emergence of mechanics and mathematics on the one hand and thanks to artists carrying out research into visual experience and technique on the other.

It is very probable that *Leonardo* was aware of the treatises of *Bacon* and *Peckham*, whose *Perspectiva communis* would have been reprinted in 1482 in Milan (41). In any event the manuscripts of *Leonardo* reflect the uncertainties of his era concerning the propagation of light rays, ophthalmic anatomy, and visual optics.

C – The Radiation Theories according the 'Perspectiva'

For *Bacon* and his successors, the general law of nature required that all natural events produced emanations or multiplications of *species*. The objects emit these species in all directions across the transparent milieu surrounding them. They converge following rigid straight lines to form a *radiant pyramid*, the visible object and the summit forming a basis encompassing every point of the transparent medium including the observer's eye. The air was thus filled with *species* originating from all objects in the visible environment. The observer perceived these *species* by one of his six external senses (and his two internal senses).

40. Bacon Roger (1210 - 1224); Peckham John (1230 - 1292).
41. According to Strong, who indicates similarities between Bacon and Leonardo. (Strong 1967, p.325 a. f.). One could challenge the comment that the 'little peasant' did not know Latin. According to Laurenza (2000), Leonardo would have learned Latin by the age of thirty-five, without, at any time, being able to write in that language.

The nature of the *species* was the object of academic debates. For example, according to *Aristotle*, the *specie* of light was a body, for *Bacon*, a worthy interpreter of *Alhazen*, it was a *similitude*, or "likeness" of the emitting body. The *similitudes* were reflected whenever they met a surface that interrupted their propagation and would be refracted when they struck a transparent surface of different density at an oblique angle. *Species* perpendicular to the transparent surface crossed it without deviation. And so, following *Alhazen*, *Bacon* emphasized that only those rays which have a perpendicular incidence enter and traverse the ocular media in order to stimulate vision; this fact simplified the intraocular passage of rays when he geometrised the eye.

D – The Eye according the 'Perspectiva'

The Latin translation of *Alhazen (De aspectibus)*, which *Bacon* completed in his *Perspectiva*, was at the origin of the geometrisation of the eye that for centuries has influenced theories concerning ophthalmic light diagrams.

Bacon cited *Avicenna, Constantine and Alhazen* and concluded that the eye is constituted of three tunics, three humors and a web:

The three tunics are divided into two parts, each of which is subdivided into posterior and anterior:

- The first tunic forms the retina (*rete* or *retina)* in its posterior part and this extends as a funnel from the equator of the crystalline lens to the optic disc. In the anterior part, it forms the uveal tunic, which is pierced in its center and opposite the optic nerve by the pupil.
- The second tunic comprises the *secondina* (our choroid) in its posterior part and the cornea in its anterior part.
- The third tunic, the most external tunic is formed by the sclera, in its most posterior part, and, the *consolidativa* or *conjunctiva* in its anterior part.

The three ocular humors are:

- The vitreous humor (*humor vitreus*) at the back, in narrow contact with the optic nerve,
- The crystalline humor (*humor cristallinus* or *humor glacialis anterior)*,
- The albugineous or aqueous humor (*humor albugineus)*, between the glacial humor and the cornea.

Finally, the spider's web (*tela aranea)*, which surrounds both the crystalline humor and the vitreous humor at the same time (42). The humors surrounded by the *tela aranea* constitute the glacial humor (*humor glacialis).*

Visual physiology was based on the idea of the perfection of the three spheres containing the humors, all of which centered on the geometric axis of the eye. The optic nerve, the hollow center of which was filled with aqueous humor or vitreous, opened into the eye where the images were. These, according to *Bacon*, would have traversed the ocular media perpendicularly and without crossing.

42. Depending on the era under consideration, the term "aranea" had one of two meanings: it indicated either the anterior lens capsule or a membrane surrounding the anterior lens capsule and retina together. (Lindberg, 1976, p. 238; note 141).

2.1.2 – Leonardo's Writings in the Context of the 'Perspectiva'

Optics and visual theory, essential aspects of the *Perspectiva,* were, of course, of interest to *Leonardo da Vinci* and not only because of the implications of perspective in painting and architecture. These subjects are spread throughout several of his diaries, and some are dedicated exclusively to it, for example, in his treatise "*On painting*", in Manuscript C "*Concerning light and shadow*", and of course in Manuscript D "*On the eye.*"
In the latter, *Leonardo*, true to the *Perspectiva* of *Bacon* and *Alhazen*, matches knowledge of light rays to that of the anatomy of the eye to suggest, amongst other things, the similarity of the eye to the camera obscura. From this result new uncertainties and questions, which are revealed notably in folios 3 verso and 7 recto.

A - Leonardo's Radiation Theory

Leonardo held to the notion of the radiation theory as contained in the *Perspectiva* and accepted that these *species* or *similitudes* propagated themselves in every direction across the transparent environment:

"The objects poured out all of their species throughout all of the air as seen by these objects. All of these species are in all of the so-called air and are in every part of it."

"li obiettj anno le loro spetie infuse in tutta l aria da essi obbiettj veduta. Lequalj spetie son tutta in tutta la perdetta aria e sson tutte in ognj parte di qlla." (43)

Leonardo converted the radiant pyramid emanating from the objects of regard into a *visual pyramid*. We have seen examples of this in Manuscript K and the Codex atlanticus. *Leonardo* also argues that vision is more precise along the central line of entry of light into the eye and diminishes as the distance of the object from this line increases.

At the same time, he does not have any exclusive preference for this theory that is called the "*intromission*" or "*radiant theory*". He described some of the other theories including that of "*extramission*" that was that the rays were sent out from the eye of the observer towards the object of regard. He cited as proof of this latter theory the regard given by certain animals that would be capable of killing, or the regard of young girls that make in the course of falling in love. Using more general terms, he compared the look to that of musk emitted by deer and which traveled long distances across the terrain.

Hesitating in his choice of explanation, *Leonardo* sometimes considered vision to be a reciprocal relationship between the eye and the object: the eye sees the object and the object sees the eye:

"Each point of the pupil sees all of the object and every point of the object views all of the pupil."

"Ognj pûto della popilla vede tutto l obbietto e ognj pûto dell obbiecto vede tutta la popilla." (44)

In folio 6 recto of Manuscript D, *Leonardo* explains in the same way that the sun sees the water and how the water sees the sun.

43. Manuscript D, folio 10 verso.
44. Manuscript D, folio 2 verso.

According to *Lindberg*, the extramission theory of *Leonardo da Vinci* must have prevailed between 1480 and 1490, while the intramission theory prevailed from 1492 (45). In fact, the analysis of Manuscript D does not allow such a clear-cut opinion, as certain passages contained therein still have ideas of extramission at the later date. The vocabulary translated these uncertainties as shown in the analysis of folios 3 verso and 7 verso. The terms *similitudes, eidola, spetie,* and *simulacra* are interchangeable and characterize the ambiguity and imprecision of *Leonardo's* language. Notwithstanding, *Leonardo* always returns to the intromission theory, because it allowed him to explain the projection of the image in the camera obscura.

B - Leonardo's Eye Representations

B.1 - The Spheres of the Eye

Leonardo, has adopted the *Perspectiva's* eye, that, according him, consists of three interlocking spheres:

The first, which he rarely includes in his diagrams or only partially, is the *sphera consolidata* or sclera, of which the anterior part constitutes the *luce* or *sphera luce.* This is represented, as seen above, in three figures of Manuscript D: twice in folio 3 recto and once in folio 3 verso.

The second, that is the largest of the three spheres, is the *albugineous sphere* that he refers to also as the *uveal sphere.* It contains the *albugineous humor* or aqueous which has low optical density.

The third sphere is the *crystalline sphere* or sphere of the *vitreous humor* and is formed from the vitreous and the crystalline lens. It is concentric with the albugineous sphere of the aqueous. The density of the crystalline sphere is higher than that of the albugineous humor and would vary with the brightness of illumination and would increase towards its center.

Generally speaking, *Leonardo* used to simplify his eye diagrams, especially the humors. The connection of these with the sphere of the *luce* is often omitted.

B.2 - The 'luce' of the Eye

The terms "*luce*", "*sphera luce*", "*lucie*", "*pupilla*" have given difficulties to translators who typically translate them by *cornea*, or at other times by the terms *pupil* or *light.* Others use them indiscriminately and this is at the origin of incorrect and variable interpretations (46).

In the course of *Leonardo's* **first period**, the terms *popilla* and *luce* are almost synonymous and more or less interchangeable. Eye diagrams before 1500 do not show a prominent cornea, the pupil is often stuck to the cornea and therefore confused with it.
In the course of his **later period** and the epoch of the publication of Manuscript D, there is a distinction between the cornea (*luce*) and the pupil (*popilla*). The term *luce* is then restricted to cornea or that part of the eye, which has a shiny appearance.

45. Lindberg 1976, p. 159-160.
46. For this interpretation, see Strong, 1967, p.97 & p.108 and Corbeau, 1964 p.100.

Diagrams, particularly those of Manuscript K and the Codex atlanticus that were cited above show that the *luce* (cornea) is that part of the eye, which is exposed in front of the globe, like a projection. In these passages, the *luce of the eye* is prominent and also convex in order to allow visualization of the peripheral visual field. The pupil is situated at the center of the base of the corneal sphere:

"The pupil of the eye is situated in the middle of the luce, which forms part of a sphere and which receives the pupil in the middle of its base."

"Lapopilla dellochio essituata in mezo alla luce laqua sta in forma di portione di spera la qual m nelmezo della sua basa riceue lapopilla." (47)

and also:

"Nature has made the superficies of the luce by placing it in the eye as a convex structure in order that objects in the environment can imprint their similitudes over a large angle which could not happen if the eye were flat."

"Fecie la natura la superfitie della lucie posta ochio q figlura conessa accio che lle cose circhustanti possino onpremere co pin grossi angholi le lor asimilitudhj il che interuenire no potrebbe essendo l ochio piano." (48)

The pupil is the door (*la porta della popilla*) of entry for rays approaching the globe. Hence, it was necessary to emphasize the optical function, the term *sphera luce* is also used as a synonym of *luce*. The term indicates that, in these instances, the segment of sphere in the form of a plano-convex lens formed by the forward projection of the cornea with the anterior chamber in the middle and the pupil behind. *Leonardo da Vinci* gives great emphasis at this time to the convexity of the cornea, to which he attributes the enlargement of the visual field.

B.3 - The Crystalline Lens

Following tradition, *Leonardo* erroneously positioned the crystalline lens in the center of the eye, concentric with the other spheres:

"The center of the crystalline sphere is concentric with the uveal sphere."

"Il cietro della spera cristalljna e concentricacol centro della spera dell ughea." (49)

We can ask ourselves why these errors occurred, given that we know that *Leonardo*, has certainly dissected animal eyes, also human eyes probably and that already *Alhazen* had placed the crystalline lens at the intersection of the corneal sphere and the uveal sphere. In folio 119 recto of Manuscript K, there is a reasonable explanation:

"Nella noto .mia dellochio per bemuerderlo dentro sanza uersare il suo omore sibede mettere lochio intero inciara doua efar bollire e soda cholio tagliare ellochio attraver so aco cella meza parte di sotto non versi nvlla." (50)

47. Manuscript K, folio 119 recto.
48. Manuscript D, folio 4 recto.
49. Manuscript D, folio 7 verso.
50. Manuscript K, folio 119 recto.

"When you want to look inside an eye without spilling its humor you should place the whole eye in egg white and bring it to the boil till solid, cut across the eye with oil in its middle part from below so that nothing flows out."

It is obvious to all present-day anatomists that boiling an eye, even after its encasement, liquefies the vitreous, mixes it with aqueous, breaks the zonules, changes the shape of the lens into a sphere, and displaces the lens to the center of the globe. This error persisted till the 17th century when the dissection of frozen eyes (51) allowed the observation of more normal relationships.

The central position of the crystalline lens made it difficult to compare the eye to a camera obscura and the lens to a refractive device. *Leonardo* therefore searched for other solutions. In the study of one of these, *the uveal theory,* he was able to match the central position of the crystalline lens, which was the organ for the perception of the *similitudes,* with the visualization of the peripheral visual field, but this demanded the reflection of light rays on the albugineous shell of the choroid. This is what *Leonardo* was explaining with his catadioptric experiments of folio 7 verso of Manuscript D.

B.4 - The Optic Nerve

Amongst other individual points, we must remember that *Leonardo da Vinci* placed the optic nerve head at the posterior end of the globe opposite to the pupil. Many of his contemporaries did likewise. By aligning the axis of the eye with the center of the disc, he attributed paradoxically the best possible perception of light to the blind spot area as was described by *Mariotte.* Like his contemporaries, he also accepted that the optic nerve was hollow and contained a humor similar to vitreous, which conducted the *specie* towards the cerebral ventricles.

C – Leonardo's Geometrisation of the Eye, the Camera Obscura and the Righting of the inverted Images

C.1 - Making a Model of the Eye

In folio 3 verso of Manuscript D, *Leonardo* proposed the construction of a model eye, also known as an artificial eye. The likely dimensions of this model have puzzled me. *Leonardo* adopted the *braccia* as unit of measurement, but this unit represented significantly large differences according to regions, countries and cities (52). Rather than use equivalent standard measurements (53), I propose to study the diagram by relating its dimensions to those of the human head for which one can assume a vertical diameter of 20 centimeters.

Diameter in centimeters	Head	Large sphere	Little sphere
Diagram	0.13	0.285	0.09
Extrapolation	20	46	14

I deduce from this, that a sphere of blown glass of about 50 centimeters in diameter, which includes an opening of 20 centimeters for the head, would appear reasonable and realizable for *Leonardo*'s time.

51. In particular by Descartes, then François-Pourfour du Petit.
52. I checked 132 local 'country areas ells', in German-speaking jurisdictions (between 0.56 meter for Saxony and 0.83 meter for Bavaria!).
53. It would be futile to translate "bracchia" by 'yards' (as Ferrero,1952 when he attributed 0,914 meter to it) nor should one adopt the French 'brasse' that is equal to 1,624 meters. Linked to the dimensions of the head, Leonardo unit of measurement, translated into French by 'brasse' would correspond approximately between 0.60 and 0.70 meter or an 'ell' (see note 3, p.11).

C.2 - The Camera Obscura, a Model for the Instrument of the Eye

(Figure 1-20)

People have claimed that *Leonardo was* the inventor of the camera obscura or of the principle of the pinhole camera. They have cited Manuscript D as the source of the corresponding descriptions. These allegations are in error, for it has been well established that the concept of the camera obscura goes back at least to *Alhazen* and was taken up by *Bacon* in "*De speculis comburantibus*" (54).

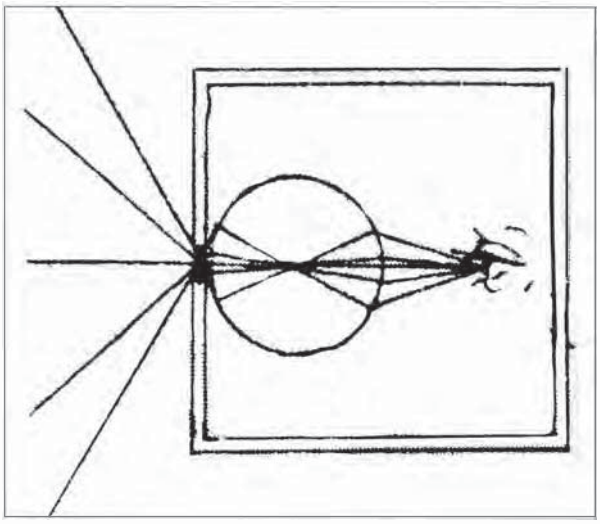


Figure 1 - 20

Leonardo da Vinci. Codex atlanticus, folio 337 recto. An artificial eye in the form of a camera obscura.

This diagram should be placed in parallel with that of the artificial eye of folio 3 verso of Manuscript D, where the eye of an observer is equally localized in the position such that it can observe the image of the similitudes on the posterior surface of the subtle glass ball representing the crystalline lens. A first crossing of the rays is produced in the pupil, a second in the crystalline lens. In this way, the optic nerve perceives an erect image at the posterior surface of the crystalline lens.

Leonardo has described his experiments with the camera obscura several times over (55). In any event, if one explores the writings of *Leonardo* in depth, one is struck by the idea that he only had an elementary understanding of the basic principles of the camera obscura. He knew that light, according to the theory of the radiation of light rays, went through a small opening in a straight line. He knew equally well that there was a relationship between the distance of the object and the distance of the screen, and he was absolutely and without doubt aware that the projected image was an inverted image. He knew also that the opening into the black chamber had to be small. However, he did not offer any theory to explain this phenomenon (56).
The connection between the inverted image in the camera obscura and the upright image that the observer perceives was at the crux of the questions which confronted *Leonardo* and which caused him to propound some of his most far-fetched theories:

"How the species from any body which pass into the eye by any tiny air hole attach themselves above and below the pupil and the senses perceives them directly."

"Come le spetie di qualûche corpo che per alcuno spirachulo passano all ochio s imprema sottosopera nella sua popilla e l senso le vedere diritte." (57)

Leonardo was the first person to insist in specific terms on the analogy between the camera obscura and the eye. This concept is explained in Manuscript D, but equally in the Codex atlanticus in folio 337 recto/a (approximately 1490-1495) where the eye is represented as having a mechanism equivalent to the camera obscura.

54. According to Hammond (1981), Russel (1997) and Lindberg (1997).
55. In particular at folios 2 verso, 8 recto and 10 recto of Manuscript D.
56. The solution will be given by Kepler. (see Chapter II: René Descartes' Contact Tube).
57. Manuscript D, folio 2 verso.

Thus, the credit comes back to *Leonardo* for his being the first to have compared the eye to a camera obscura. This analogy was challenged in any event by two major objections. The first objection is that the projected image at the bottom of a black chamber is inverted, whereas the human observer perceives the image as upright and corresponding with the normal world. The second objection is that the eye is spherical whereas the bottom of the camera obscura should be flat in order to obtain a sharp image conforming to the laws of perspective.

Because of this, *Leonardo da Vinci* did not happen to propose the projection of the image on the retina. He imagined, in contrast, that the projection of the image occurred on the optic nerve head, precisely on the optic papilla, which corresponds to the blind spot of *Mariotte.* For that, he relied on two erroneous arguments which had already been propounded by *Bacon* following *Alhazen:* first that only those light rays perpendicular to the corneal and crystalline lens surfaces, then passing along the axis of the globe, would reach their destination intact, and secondly that the optic nerve head was situated at the junction of the geometric axis of the eye and the fundus and exactly opposite to the pupil.

Leonardo, however, could not accept this theory because images were received from the peripheral visual field, from which came the explanations, in particular from folio 18 verso of Manuscript K and folio 222 recto/a of Codex atlanticus, where he attributed the role of peripheral visual ray collector to the *luce*, the dome of the anterior segment of the eye.

Leonardo da Vinci did not make a frank pronouncement on the suggestions of *Alhazen*, of *Bacon* and their successors, according to which the vitreous or albugineous humor, which would fill the central cavities of the optic nerve, would transmit the luminous impressions to the brain. In any event, he suggested the possibility that the eye and the cerebral ventricles constituted the elements of a unique camera obscura, linked by a kind of optical fibers, and composed of a humor that was enclosed in the hollow center of the optic nerve.

C.3 - Leonardo's Two Theories of an intraocular Changing of inverted Images to Upright

The likening of the eye to the camera obscura by *Leonardo* caused him to research intraocular intersections of light rays that would rectify the projected inverted image so that it was perceived as upright. The idea of an intersection of light rays is an innovation of *Leonardo* because no treatise of *Perspectiva* mentions intraocular crossings. According to *Russell* (58), only *Alhazen* proposed the idea of a second refraction at the posterior surface of the crystalline lens, but his proposal was without conviction.

In Manuscript D, *Leonardo* proposed two sets of solutions for correcting the inverted image according to the principles of the camera obscura:

Firstly, the **dioptric solution** was based on the theory of double crossing of rays in the crystalline lens, where refraction was produced either in, or behind, the crystalline lens (shown amongst others in folio 3 verso of Manuscript D). This theory of crossing in the central area of the eye clearly did not satisfy *Leonardo*, because it did not allow him to explain the perception of objects in the peripheral visual field.

58. Russel 1997, p. 348 - 350.

And secondly, the **catadioptric solution**, based on the *uveal theory*, where the rays striking the uveal sphere caused a change of the inverted images to upright, because this sphere acted like a concave mirror (explained in folio 7 verso, illustrated equally in folio 119 recto of Manuscript K). As far as *Leonardo* was concerned, this proposition, even if it allowed an explanation of the peripheral visual field, partially contradicted his own observations with the camera obscura in which rays of light pass through a pinhole aperture in order to project onto the posterior wall.

D - Perception of the peripheral Visual Field made possible by the Convexity of the 'luce'
(Figure 1-21)

Leonardo tried to explain the perception of the peripheral visual field by the convexity of the dome of the *luce*, which term encompassed in this context both the cornea and the aqueous humor of the anterior chamber. According to the *Perspectiva*, only the straight light rays, which are perpendicular to a transparent substance, passed through this substance without either being reflected or refracted. Moreover, as we see up to *almost behind the shoulders*, that could be because the curvature of the *luce* captures the *spetie* coming from the peripheral visual field, *breaks* them up and sends them towards the pupil. *Leonardo* proposed several experiments to indicate the extension of the visual field across a convex cup. This produced the interesting diagrams, from both, folio 118 of Manuscript K, and folio 222 recto/a of the Codex atlanticus, of placement of glass cupolas in front of the eye or face, positioned to focus rays on the pupil.

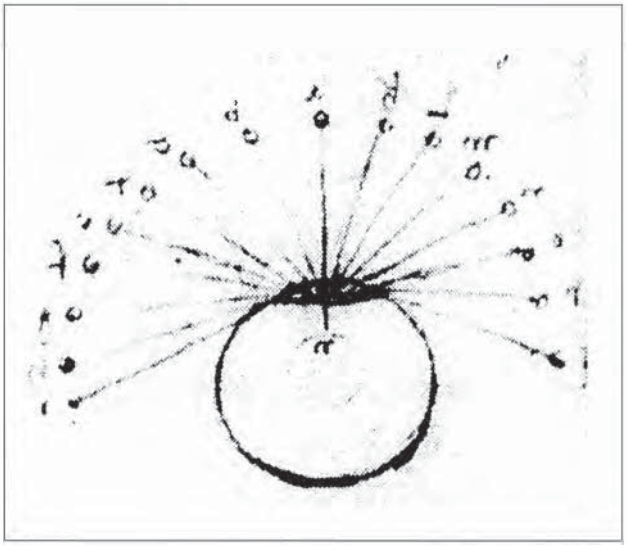


Figure 1 - 21

Leonardo da Vinci. Manuscript D, folio 8 verso. Incidence on the corneal dome on the rays of similitudes coming from the peripheral visual field.

The corneal dome of the luce of the eye is striking for the fact that "the eye sees those objects behind it which are placed in lateral areas" (l'ochio vede dirieto a sse cose posste nelli spati laterali -Manuscript D, folio 8 verso). Alone the perpendicular ray in the center of the cornea crosses the pupil. The crystalline lens is placed in a central position.

The diagrams and the texts of folio 222 recto/a of the Codex atlanticus are particularly revealing. Thus, by means of the experiment described at **the bottom** of the folio, *Leonardo* purported to show that a convex structure enlarged the visual field, like a photographic wide- angle lens. Such a structure would allow the subject to see *behind the shoulders* in the same way as the convexity of the cornea, at the surface of the eye, makes the rays of light converge from space from *"as far back as the ears"* towards the pupil, as described **above** in the same folio.

According to theories accepted at the time, only those rays that fell perpendicularly on the eye, could enter. Without calling into question this dogma, *Leonardo da Vinci* observed that rays coming from lateral space, *as far back as the ears,* were equally well perceived. He searched for an explanation by evoking the refraction of rays as they were passing through the corneal dome. He proposed performing the experiment of the facial hemisphere as an argument in favor of this hypothesis.

The convexity of the *luce of the eye* and its role in the perception of the peripheral visual field by focusing rays on the pupil is a theme, which has been touched on several times by *Leonardo*. Thus in folio 8 verso of Manuscript D, he wrote:

"The eye has in itself a single line which is called the central line, and all the spetie from objects which come by the eye along this line are visualized perfectly [...]. Around this line, there is an infinite number of particles that are adjacent to it and that have a value which is larger or smaller depending on whether they are nearer to or farther from the center."

"L ochio a in se vna sola linja la quale e detta centrale e ttutto le spetie delli obbietti che venghano all ocho per essa linja sono perfectamête vedute [...] Dintorno a essa linja ne sono infinjte aderenti a cquella le quali son di tanta magore ô minor valitudine quanto esse sono piu vicine o vremote a ttal centrale." (59)

In folio 118 verso of Manuscript K, *Leonardo* recommended *"to see what function the luce performs for the pupil, made out of crystal an object similar to the luce of the eye"* (60), which would be placed in front of the eye. The diagram adjacent to this shows a cup or a small lens, flat surface posterior, convexity anterior and behind these, there is a drawing of the inside view of an eye. In front of its convex anterior surface are the convergent rays.

59. Manuscript D, folio 8 verso.
60. "Per uedere chevfitio fa la luce alla popilla fafare di cristallo una cosa simile alla luce dellochio" (Manuscript K, folio 118 verso).

2.2 - Leonardo da Vinci, a Genial Inventor or a Witness of his Times?

Leonardo was apparently the first to express the pathway of the rays in the eye in terms of refraction and reflection and to be very mechanistic in his conception of the eye and of the visual process. If he easily enunciated mechanistic explanations of the visual intraocular process by reducing the crystalline lens to an instrument of a certain dioptric power and the uvea to a reflecting mirror, his notes nevertheless show hesitation, uncertainty, and a troubling confusion. Furthermore, none of the theories advanced is capable of producing the expected changing of the inverted images to upright ones and of reconciling, by means of an intraocular phenomenon, the known inversion of the images in the camera obscura and an upright perception of the world by the eye.

The folios of Manuscripts D and K and of the Codex atlanticus appear therefore like an inventory of ideas in process, which allow us to have a view of optical problems, which had not been solved at the beginning of the 16th century. *Leonardo* often included speculations, from which, with an effort of imagination, one could predict the outpouring of solutions found in later times. The most significant innovations found in the analyzed folios below are the concept of the eye as a camera obscura and the intersection of light rays in the interior of the eye.

In order to conclude this overview, I have enumerated the principal contributions of *Leonardo da Vinci* to anatomy, physiology and ocular optics contained in the folios analyzed below.

Thus, one can state that *Leonardo:*

- Presented a description of ocular anatomy founded on a geometric and mechanistic approach, inspired by *Bacon* and *Alhazen*.
- Likened the eye to a camera obscura, the pupillary aperture corresponding to the aperture of this camera.
- Reduced the crystalline lens to a dioptric instrument, although the intersection of rays in the substance of the crystalline lens only constituted one of the different alternatives proposed.
- Described the variability of the pupillary diameter as depending on the intensity of illumination, but incorrectly related pupillary motility to visualization of the image size by the cornea.
- Drew attention to the role of the optic nerve in the retroocular transmission of luminous perceptions, but routed this transmission via a hollow nerve towards the *"ventricle situated in the human brain"*.
- Described the importance of the convexity of the corneal dome and anterior chamber in the perception of the peripheral visual field.

His mistakes would be too numerous to mention if one were to be permitted to judge *Leonardo* according to the standards of today's knowledge. This would however be quite unjust because, in general, he recorded more or less honestly the ideas, doubts, and uncertainties of his era.

2.3 - The Impact of Leonardo da Vinci and his Legacy

It cannot be sufficiently emphasized that *Leonardo* did not publish his ideas and does not appear to have applied them practically. He had no university education, and although he was endowed with an acute sense of observation, and inventive spirit and a philosophical turn of mind, he was handicapped by his incapacity to communicate in Latin. For this reason, he kept what he imagined to himself.

He received his basic education as an apprentice at *Verrocchio's* studio, under the tutelage of the painter, sculptor and jeweler. Here he learned the art of perspective and his understanding of mechanical contrivances. Self-taught, *Leonardo da Vinci* collected scientific and literary books. As *Laurenza* described, many of his artistic creations were the fruits of an assimilation of the concepts of medieval and classical natural philosophy, a good part of which was accessible only in Latin. *Leonardo* wanted to learn the Latin language, but in spite of all efforts, he never mastered it and had to call on the help of an educated friend in order to translate difficult passages (61).

As an artist, *Leonardo da Vinci* was intrigued by light, but unlike other artists tried to study in greater depth the questions of reflection and refraction of light, specifically as it crossed into and through the eye. As an artist, he also had to familiarize himself with anatomy, and this led him to dissecting which was still a difficult activity at his time. He did not share his knowledge, published no drawing or article, and made no effort to publicize his activities, notwithstanding that both printing and etching were readily available to him (62).

61. According to Laurenza 2000, p. 21-29.
62. See Keele (1955), Ehrich (1979), Hoang (1984), Boullaud (1987), Laurenza (2000) and Ehrich & Heitz (1988), Heitz (1984, 1998) and Heitz & Enoch (1987).

3 – Leonardo da Vinci, Neutralization of the Corneal Dioptric Power and Contact Lenses

Leonardo is often described as a prophetic scientific genius, "ahead of his time", who was also at the origin of the invention of contact lenses or of their underlying principle, the neutralization of corneal refractive power.

The alleged References to Corneal Dioptric Power Neutralization

3.1 - Folios 3 verso and 7 verso of Manuscript D

In fact, one can find in folio 3 verso and 7 verso of Manuscript D sketches representing faces and eyes submerged inside devices, cups and cupolas, filled with water. Taken out of their context, these drawings could make a person believe that they indicated neutralization of corneal dioptric power along with the adjunction of refractive surfaces.

However, the analysis of the texts and the drawings indicates that this is definitely not the true situation, according to the available facts. Nowhere, in these passages, did Leonardo evoke the subject of a possible neutralization of corneal dioptric power by a liquid placed in contact with the face or eyes, nor the substitution of a new dioptric element to the dioptric power thus neutralized.

3.1.1 - Folio 3 verso

The diagram of a face immersed within an optical structure of **folio 3 verso** of Manuscript D illustrates, as we have seen, a proposal relating to the construction of an artificial eye. The observer would have his face submerged in such a way that his eye would be at the precise position of the optic nerve head and would therefore see the image projected in the crystalline lens according to the erroneous theory of intersection of rays introduced by *Leonardo da Vinci* in folio 2 verso.

Keele shares this explanation in the legend under the figure of the schema of "*the artificial eye*":

"*Leonardo's experiment in which the human eye takes the place of the optic nerve in a glass model of the eyeball with its lens, the whole apparatus being made to fit on to the head of the observer. A diagram of the paths of light through the eye is drawn below, the corresponding paths of light in the model above.*" (63)

3.1.2 - Folio 7 verso

The diagram of cupolas and of spherical shells sketched in **folio 7 verso** illustrate the uveal theory, that is to say, the erroneous theory of the inversion of an image by reflection on the concave "mirror" of the uvea. *Leonardo* used spherical glass surfaces to demonstrate the mirror effect attributed to the concavity of the uvea, thought to reflect and correct from

63. Keele 1955, p. 385 figure 2.

inverted to upright the images projected as inverted images within the eye, according to the principle of the camera obscura. Both legends and context show clearly that the diagram concerns catadioptric experiments with spherical mirrors and not glass cups with an optical effect.

Indeed, *Leonardo* described in this Manuscript D folio, a face and eyes immersed in a liquid contained in an artificial eye, and also in cups, cupolas, and eyecups, centered on, and sometimes fixed on the optical axis. They are theoretical and speculative descriptions that he advanced in order to illustrate his dioptric and catadioptric theories, which he proposed in order to convert, from inverted to upright, the inverted image in an eye represented as a camera obscura. No document allows us to declare that these structures were ever tried out in practice, under which circumstances besides, they would not have had the expected effect.

These immersions do not have any connection with contact lenses, even if it were admitted that immersing the face or the eyes in optical devices, cups, eyecups or cupolas filled with water, would produce a neutralization of corneal refractive power. This effect however is not researched, asserted, or described. In no text of Manuscript D did *Leonardo* reveal an inkling of the interest or significance of corneal neutralization.

3.2 - Folio 118 verso of Manuscript K

The structure of the "*object of crystal*", drawn on folio 118 verso of Manuscript K and supplemented by the text of the same and following folios, definitely showed a plano-convex lens. This lens placed in front and at a certain distance from the eye, had to collect the peripheral spatial images and focus them on the pupil just as "*the luce takes all the similitudes of objects of regard and sends them to the pupil*". The lens of crystal permitted an individual to view objects "*as far as behind the shoulders*". In spite of the apparent resemblance of the drawing to a modern contact lens, *Leonardo* was not, in fact, describing a contact lens (64).

3.3 - Folio 222 recto/a of Codex atlanticus

The proposition expressed in folio 222 recto/a of the Codex atlanticus describes a hemispherical cup filled with water, hermetically sealed and placed on the face. It indicates, without any doubt, an immersion in a water-bath maintained by a watertight hemispherical glass shell.

The experiment is intended to demonstrate, in addition to the dioptric neutralization of the "*luce of the eye*", the replacement of the neutralized surfaces by the new surface of the hemispherical shell to which *Leonardo* attributed a dioptric effect because, as he states, "*thou shall see those things that are seen from the surface of this bowl.*"

The immersion means moreover the total immersion of the face of the observer, as is also shown in the neighboring drawing also shows, in which we recognize the side view of a face. The aim of the demonstration would not be to correct a refractive error, but to explain

64. See the analysis of this passage by Ehrich & Heitz, 1988.

the convergence at the pupil of the *species* coming from the periphery of the visual field. If *Leonardo* had utilized the neutralization of the cornea and the replacement of the neutralized dioptric power by the curvature of the glass hemisphere in this demonstration, this would have been unintentional, because such was not the object of his description. Both the text and the diagram of folio 222 recto/a of the Codex atlanticus do not justify the recognition of *Leonardo* as the first actually to discover these two essential characteristics of contact lenses.

It is however possible that, according to the wording contained in folio 222 recto/a, *Leonardo* would have realized that water contained in the facial hemisphere has transferred the surface of the *luce of the eye* towards the surface of the hemisphere, because *"the things are seen from the surface of this bowl"*.
Clearly, we are concerned with a speculative proposition with has originated in the imagination of its author. The experiment is impractical and unrealizable: no system for the maintenance of respiration was foreseen and there was no reference to a hermetic seal for the periphery of the hemisphere.

This proposition contained in folio 222 recto/a is not linked with the facial or ocular immersion experiments of folio 7 verso of Manuscript D. *Leonardo* did not propose, for the experiments in the Codex atlanticus, the utilization of cups or shells of the smallest size to be placed in front of the eye or the orbit, such as he described in folio 7 verso of Manuscript D for the experiments with concave and convex mirrors. If he had made a connection between the ideas expressed in the two documents, he would perhaps have been able to describe more precisely the neutralization of the dioptric power of an eye and its replacement by a new optical surface.

Thus they are propositions, all of them theoretical and speculative, of a system of immersion of the face in a liquid maintained by a giant shell and of the replacement of the dioptric power neutralized in the two eyes by the surface of this hemispheric shell. The extrapolation of this experimental proposition to the principle of contact lenses is questionable and must be subject to the following provisos:

- The glass hemisphere was not placed on the eye, but covered the face, as described in the text and illustrated in the adjacent drawing. It is thus a facial immersion and not an ocular immersion.
- The glass hemisphere was not intended to correct a refractive error, but only to demonstrate that a transparent convex surface filled with water allowed rays from the peripheral visual field to focus on the pupil after refraction, as they passed through two media of different refractive index.

Leonardo has therefore made a theoretical proposition, undoubtedly interesting, but extremely difficult, if not impossible, to realize or prove in an experiment.

4 – A short History of the Origin and the Propagation of several Misinterpretations

Manuscripts D and K and the Codex atlanticus of *Leonardo da Vinci,* as studied above, describe respectively the immersion of the face, or one or two eyes in water-containing devices which are centered on the optical axis. *Leonardo's* descriptions are always theoretical and speculative propositions, originating in his fertile imagination, while he was attempting to explain the contradictions of the interpretations of optics at the beginning of the 16th century.

Following the objectives, which *Leonardo da Vinci* determined to demonstrate, he utilized various procedures as:

- Immersion **of the head**, as shown in description of:
  - the complex device as "*artificial eye*" (Manuscript D, folio 3 verso),
  - a pre-facial cup from which he expected a mirror effect (Manuscript D, folio 7 verso),
  - a cup from which he expected a "*wide angle*" periscopic vision (Codex atlanticus, folio 222 recto/a).

- Immersion **of only one eye** in the "*occiali*", as shown by miniaturized experiments with pre-facial mirrors (Manuscript D, folio 7 verso).

- The **addition in front of the eye** of an "*artificial cornea*" in the form of a plano-convex lens, with a wide-angle effect (Manuscript K, folio 118 verso).

At the time of the immersion experiments of Manuscripts D and K, whether their purpose may have been, catadioptric or perimetric, the neutralization of corneal dioptric power was not intentionally researched. Only the text of the Codex atlanticus mentions that the surface of the shell, under which the face was submerged, would replace the corneal surface, and this would lead us to assume that *Leonardo* accepted its neutralization. Reference to Manuscripts D and K in order to designate *Leonardo* as inventor of the principle on corneal diopter neutralization is unjustified. Reference to the Codex atlanticus however, and taking account of certain reservations, would be less contestable. In any event, this citation, while sometimes omitted, is also the object of equivocal or confusing interpretations. Without claiming to be exhaustive, I am going to attempt, in this chapter, to go back to the origin of these errors and misunderstandings and analyze how they came to be disseminated.

4.1 - The false Interpretations of the Extracts of Manuscript D

The drawings of immersions in folios 3 verso and 7 verso of Manuscript D are often utilized in order to attribute to *Leonardo* the invention of the principle of contact lenses. These erroneous attributions only appeared in the course of the second half of the 20th century. The first of them could be attributed to *Hofstetter* and *Graham* (1953). These authors, without having consulted the documents of *Leonardo*, used a free translation of Manuscript D by *Ferrero*, which was published in the American Journal of Ophthalmology (65). They deduced from it that *"In two separate instances Leonardo employed the optical method of immersing the eye (or eyes) in a lens containing water"* (66).

They illustrated their argument by the reproduction of drawings from the margin of folio 3 verso representing an *"artificial eye"* and from folio 7 verso of facial and ocular immersions (67). The argument, extended to other would-be inventors *(Descartes, Hershel)* was taken up then by *Graham* and by *Enoch* (68). The error was introduced into the German-speaking literature in a summary by *Samland*, then in a translation into German from *Hofstetter* and *Graham* by *Abel* (69).

It would be a gigantic task, both lengthy and not of great interest, to list those authors who have repeated the errors and who have extrapolated or amplified them by unbelievable interpretations. I shall limit myself to some typical examples. For Manuscript D, these errors concern three types of diagram and their texts, as described above.

- The *"artificial eye"* from the top of folio 3 verso,
- The *"pre-facial mirrors"* in the margin of folio 7 verso,
- The *"occhiali"* included in the text of the lower part of folio 7 verso.

It happens also that these historians mix up the citations extracted from these three passages or that they juxtapose the citations from one of the folios with the diagrams of another (70).

65. Ferrero, 1952.
66. Hofstetter & Graham, 1953, p. 41.
67. However Keele (1955) published an accurate interpretation in the following year, which unfortunately was not noticed by these authors.
68. Graham is more guarded in 1959 than he was in his preceding publication: "Leonardo da Vinci was the first person to conceive of neutralizing the cornea and substituting for it a new refracting surface. About A.D. 1508, he described several forms of contact lenses, which would accomplish this result. Some of his devices were enormous and complex; some were tiny and simple. He did not describe corneal lenses but did suggest the principle upon which they, as well as scleral lenses function. Accordingly, both types of contact lenses may be said to have had their inception with da Vinci" (Graham 1959, p. 55). For Knoll (1980) these arguments served to refute the priority of the patents claimed by manufacturing companies on corneal contact lenses at the time of a court case against Graham.
69. Samland (1966), Abel & Thiele (1968).
70. The most common amalgamation consists of illustrating a quotation of folio 7 verso by the diagram of the artificial eye of folio 3 verso.

4.1.1 - Errors relating to 'Artificial Eye' of Manuscript D, Folio 3 verso

(Figure 1-22)

The erroneous interpretation of *Graham* was taken up, in 1970, by *Mackie* in the *System of Ophthalmology* by *Duke-Elder* and thus acquired a long undisputed authenticity:

"The germ of the idea of contact lenses was conceived by Leonardo da Vinci about 1508 who suggested immersing the eye (or eyes) in a hollow glass bowl containing water (Fig 730)." (71)

Duke-Elder illustrates this comment with the diagram of the immersion of the head in *the artificial eye*, accompanied, in the legend, by a partial translation followed by the additional comment that *"the optical system described above is, of course, not correct"*. Since that time, the error has been copied, translated, and extrapolated, each version adding new errors, without their authors verifying the authenticity.

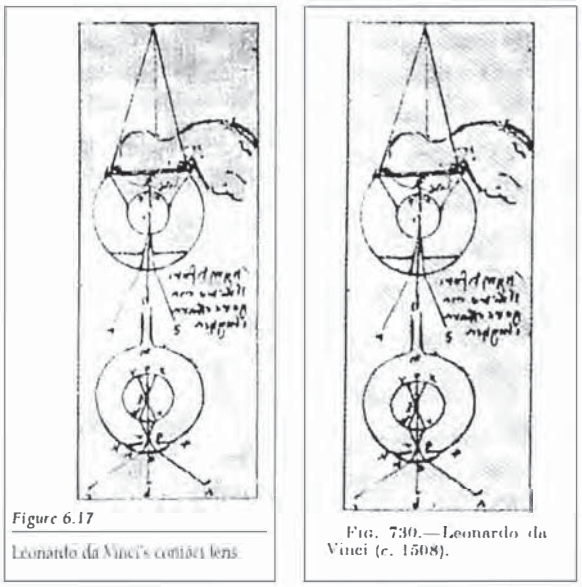


Figure 6.17
Leonardo da Vinci's contact lens

Fig. 730.—Leonardo da Vinci (*c.* 1508).

Figure 1 - 22

Erroneously equating of Leonardo da Vinci's artificial eye to a contact lens

(On the left Albert (1996, p. 120). On the right Mackie in Duke-Elder (1970, p. 715).

Subsequently, however, somewhat timid critics of these erroneous extrapolations grew up. Particularly *Sabell* and *Levene* criticized the likening of the "*artificial eye*" structure to a "*giant contact lens*":

"This globe being filled with water, into which the observer immersed his face in the optical neutralization of the observer's corneas. Other than the fact that the corneal surface is neutralized it is difficult to see precisely what relevance this has to the history of the contact lens."(72)

"This was, for da Vinci, purely a model (literally a schematic or 'artificial eye') and although superficially deceptive in its similarity, should not be confused with the concept of corneal neutralization."(73)

In spite of these corrections, the error remains still current nowadays even among historians of high reputation:

"In a manuscript dealing with the eye and optics designated "Codex of the Eye" (Manuscript D), da Vinci provided a series of drawings and notes in describing the fashioning of ampoules from balls of glass that are filled with water and applied over the cornea. Da Vinci laid the basis for the concept of the contact lens (Fig. 617)." (74)

71. Mackie in Duke-Elder 1970, p. 715. The figure 730 represents the experiment of 'the artificial eye'.
72. Sabell 1972, p. 1.
73. Levene 1977, p. 292.
74. Albert 1996, p. 120.

This ambiguous text draws on glass cups and the *"occhiali"*, but it is incorrectly illustrated by the diagram of the immersion in the *"artificial eye"* with the legend *"Leonardo da Vinci's contact lens"*.

4.1.2 - Errors relating to Facial Immersions of Manuscript D, Folio 7 verso

(Figure 1-23)

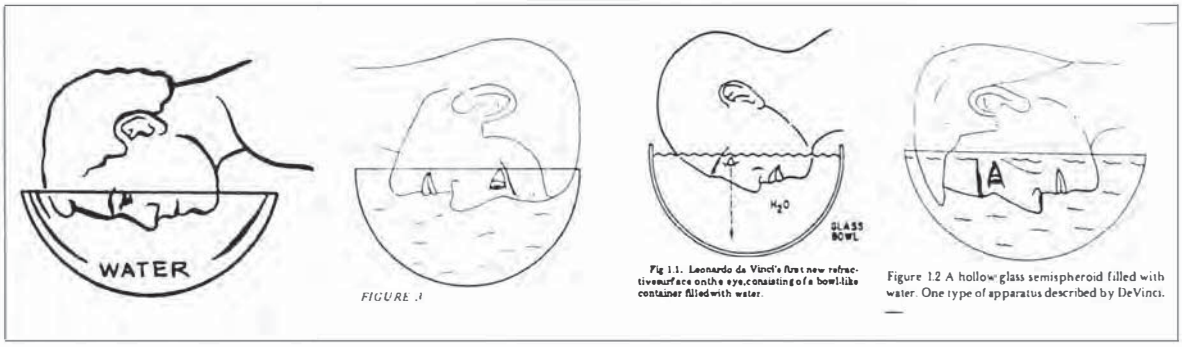


Figure 1 - 23

Dubious extrapolations of Leonardo da Vinci's facial immersions with their incorrect legend.

From left to right: Graham (1959, p. 56) Lumbroso (1977, p. 15), Hales (1978, p. 4), Mandell (1988, p. 6).

The immersion cups in the margin of folio 7 verso of Manuscript D are often cited and illustrated in more or less random fashion. According to these authors, the pre-facial shells of this folio represented lenses, which gave improved vision to the observer whose face, or eyes, were immersed in them. The context and the legends show however, without any ambiguity, that these are catadioptric experiments. Submerging the head in a spherical cup, of which the function is designated as *"mirror"* by the legend, has nothing to do with visual correction.
And so we can find the following erroneous citations:

"Leonardo da Vinci, writing in the sixteenth century, described glass cups containing water which were placed over the eye to simulate this state. They may be considered as the first contact lenses, but it is doubtful whether the full significance was understood, and they were probably used only to obscure the vision." (75)

We can read even that *Leonardo da Vinci* would have corrected a pathological corneal irregularity:

"Leonardo da Vinci (1505), was the first to have the idea to neutralize the irregular surface of a pathologic eye by a regular surface. The principle was to substitute a new refractive surface for this cornea: the immersion of the face in a hemisphere filled with water made this substitution a practical proposition."

75. Ruben 1975, p. 1.
76. Lumbroso 1977, p. 15.

« Léonard de Vinci (1505) a eu le premier l'idée de neutraliser la surface irrégulière d'un œil pathologique par une surface régulière. Le principe était de substituer à cette cornée une nouvelle surface de réfraction : l'immersion du visage dans une demi-sphère remplie d'eau réalisait cette substitution. » (76)

Or, that it was a magnifying loupe that was under consideration.

"The Italian Leonardo da Vinci (1452-1519) describes an interesting experiment in 1508: After having submerged the head in a cup filled with water, the bottom of which was a spherically-ground disc, he was able to see clearly small and even the tiniest objects. It remains however doubtful if he at that time realized the full significance of his discovery."

« Der Italiener Leonardo da Vinci (1452-1519) berichtet im Jahre 1508 über ein interessantes Experiment: Nach Eintauchen des Kopfes in eine wassergefüllte Schale, deren Boden aus einer sphärisch gekrümmten Scheibe bestand, konnten selbst kleine und kleinste Gegenstände scharf gesehen werden. Es bleibt jedoch zweifelhaft, ob er dabei bereits die volle Bedeutung seines Experiments erkannt hat. » (77).

Hofstetter himself returned to his earlier claims and admitted that, in reality the *facial* immersions of folio 3 verso and 7 verso did not represent contact lenses. Nevertheless, this late correction was not sufficient to stop the ongoing propagation of the same errors.

4.1.3 - Errors relating to 'ochiali' of Manuscript D, Folio 7 verso

For *Hofstetter and Graham*, the drawings of the "*ochiali*" included in the text at the bottom of folio 7 verso would be of special significance for contact lenses:

"The three very small drawings in the second last and fourth last lines of the legend in figure 2 may be interpreted to be simple freehand illustrations of one contact lens by itself and two in situ, i.e. in contact with the eye, the inside curve appearing to be the cornea in each illustration." (78)

This error is often repeated. An example of this is found in the Centenary special issue of the Journal of the American Academy of Ophthalmology:

"Leonardo da Vinci, the multitalented genius of the Renaissance, is credited with conceiving the basic principles (though not clinical practice) of the contact lens, to replace the corneal refracting surface, which was neutralized by the tear interface. One of his constructive approaches was to cut small round ampoules in half, fill one with water, and apply it to the eye, a procedure not unlike current contact lens practice." (79)

Hofstetter confirmed, in a recent publication, that the figurines included in the text at the bottom of folio 7 verso represented contact lenses. For him, *"in either case it is clear that Leonardo described a small lens to be placed directly on the eye as a substitute for glasses."*

"Granted that while a water-filled glass bowl in which one's face is immersed is in a generic sense a kind of bioptic contact lens, it does not convey the state of advancement of

77. Roth 1978, p. 28.
78. Hofstetteer & Graham 1953, p. 43. This argument and description was also taken up again by Enoch (1956), but he modified it at a later date (Heitz & Enoch, 1987).
79. Rubin & Hope 1996, p. S102. It is quite surprising that these authors had introduced a new error into the text, by utilizing a tear interface for corneal neutralization.

Leonardo's ingenuity. He did indeed describe a contact lens to be fit on the eye itself [...]. "*In a preceding paragraph of the bioptic face-in-water discussion, Leonardo has written (translated by Ferrero) 'And if you want to look with only one eye do use the body of a little or a big ampoule, etc.' The follow-up legend [...] then reads in its translated version as follows: 'Make little round ampoules like this' [Here is drawn a tiny glass flask] 'then cut them like glasses are cut with a hot piece of iron and make shells of half sphere like this.' [Here are drawn two crescent-shaped representations of the glass shells in an upright position.] 'Then use them for your glasses full of water like this [here is the last drawing] and fill only one with water.'*" (80)

Based on the followings citations of interchanged abstracts, *Hofstetter* clarified his reasoning

"*Two of the last three drawings may be interpreted as lenses in contact with the eye; the inside curve in each instance appearing to represent the cornea, or each may be an assembly of two spherical pieces of glass with water between. However, their vertical instead of horizontal orientation favors the former interpretation, as does the loosely woven but nevertheless persistent theme in the rest of the marginal note, that of water in contact with the eye. In no way does Leonardo imply an assembly of two spherical pieces of glass, one inside the other. The flatter inside curves in the two drawings are probably casual strokes of his pen to show the manner in which he specified would be retained inside of the lens.*" (80)

He concluded nevertheless on a reserved note leaving the door open to other interpretations:

"*Perhaps another reader of 15th century Italian can resolve this possible ambiguity better than translator Ferrero did.*" *(80)*

Hofstetter committed the very widespread error of placing his citations out of the context of the other sketches and their legends in the margin of folio 7 verso. In taking note of the parts situated directly above the cited passage, he would have noted the apparent similarities of the text, which he analyzed, and the descriptions of catadioptric experiments. He would have concluded that the experiments with the "*ochiali*" were only miniaturizations of the pre-facial mirrors. Let us recall that we are dealing with the following passages from above down:

- "*Break a glass carafe and make out of its convexities and concavities a mask full of water and you will see that what is promised below is true*" (M 2)
- "*and if you want to see with one eye only, do it with the body of a small or large ampoule etc.*" (M 3)
- "*here the air makes a concave mirror*" (M 4)
- "*here the air makes a convex mirror*" (M 6)

These catadioptric experiments, with pre-facial concave and convex mirrors, performed with a segment of a glass bowl, one of the surfaces of which is in contact with water, have to, in *Leonardo's* opinion, explain the *uveal theory* of the reflection of images on the concavity of the choroid. These experiments are followed right at the bottom of the margin (in M 7), with the experiment of the little shells and the recommendation to make "*ochiali*" (eyecups) out of them, these also being filled with water and placed in front of one eye only (as had been announced in M 3).

80. Hofstetter 1984, p. 17. It should of course read '16th century Toscan'.

The subsidiary argument of *Hofstetter*, that the vertical position of the *ochiali* would prove that "*contact lenses*" was meant, is not valid, as two of the three prefacial cups were similarly placed in a vertical position and that both their "*concave mirror*" function (in M 4) and their "*convex mirror*" function (in M 6) were very appropriately described by *Leonardo da Vinci* in the adjacent legends.

4.2 – Errors relating to Diagrams and Texts of Folio 118 recto of Manuscript K

The drawing by *Leonardo* of a plano-convex lens in front of an eye in folio 118 verso of Manuscript K is not well known. It was never cited by *Hofstetter and Graham* and was only occasionally mentioned by the contact lens historians.

Argentieri juxtaposed this figure besides that of folio 222 recto/a of Codex atlanticus, with the shared legend "*model of cornea in glass – Ms K. fol. 118 v.*" (81). In the same way, he approximated it with a diagram of Manuscript D, with the legend "*study of enormous visual field covered by the eye – Ms. D, Fol. 8 v.*" (82).

Levene continues with this thought process by recognizing an "*artificial cornea*" there, but he makes the mistake of illustrating it with a diagram of folio 33 of Manuscript F. Without having consulted the original documents, he does not hesitate to draw decisive conclusions from them, unfortunately confused. (83)

A seldom cited study by *Ehrich* (1974) led one to suppose that "*the anterior face of the cornea was not spherical, but aspherical*" (84), and that it flattened out towards the periphery. By means of this variable geometry of the corneal curvatures, *Leonardo* explained the capacity of the eye to accommodate to distance and near vision as a function of pupillary aperture (85). More recently, and in a more exhaustive study on this folio, this author no longer makes this interpretation and confirms what I have demonstrated. (86)

81. Argentieri 1956, p. 430, upper right figure.
82. Argentieri 1956, p. 430, figure in margin.
83. According to Levene (1977, note 3, page 311), and making allusion to the drawing of Ms K: "Leonardo Ms. F. 33 V. (Institut de France) cited in Keele, K.D. (1955). [...]. See also Argentieri D. (1956). "Leonardo's Optics." Leonardo da Vinci p. 430 New York Reynaldo, showing model of cornea in glass from Ms K folio 118 v. Whether or not the central glass globe was "hollow" and filled with water, or only the surrounds was filled with water, while the globe remained hollow, is difficult to interpret. For opposing interpretations, see Argentieri D (1956) Ibid p. 427 and Enoch J.M. (1956) 'Descartes' contact lens' Am. J. Optom. 30, 77." Levene is incorrect because the diagram of Manuscript K used by Argentieri on page 430 does not contain any 'central glass globe'; he seems to have mixed up the numerous drawings of 'artificial eye', probably that of folio 3 verso of Manuscript D, reproduced by Argentieri on page 428.
84. " Während die Abbildung lediglich zeigen soll, daß die Vorderfläche der Hornhaut keine Kugelfläche, sondern eine asphärische Fläche ist. " (Ehrich 1974, p. 14).
85. The theory of accommodation by dilatation and constriction of the pupillary diaphragm persisted in various guises till the 18th century (see Chapter IV: Philippe de La Hire's Ocular Contact).
86. Ehrich & Heitz, 1988.

4.3 – Errors relating to Diagrams and Texts of Folio 222 recto/a of Codex atlanticus

Levene (1977) and *Brachner* (1998), who cite the passage of folio 222 recto/a of the Codex atlanticus, make reference to citations of *Argentieri* (1939, 1956) or *Keele* (1955). The two citations, placed out of the context of the folio, show some differences and these are at the origin of the errors and misinterpretations. It is not unreasonable to suppose that this difficulty has led the majority of the historians to omit the reference to folio 222 recto/a of the Codex atlanticus.

Keele had not himself consulted the relevant folio, but a preceding Italian language article of *Argentieri* (1939) gave him his inspiration. He correctly links the experiment of folio 222 recto/a of the Codex atlanticus to the description of the *"luce"* in other manuscripts, and translated the passage:

"if you take a half a ball of glass, fill it with water, and put it close to your face, you will see all the things that can be seen from the surface of the ball; in such a way you will be able to look straight at your own shoulders". (87)

Argentieri, of whom an English translation in 1956 served as a reference for *Levene*, also made the link between the "*luce*" and the experiment described in folio 118 verso of Manuscript K, referred to above. *Argentieri*, however, provides an original interpretation. He accepts that the glass globe is in a horizontal position and that the observer inclines his head until his eyes are in contact with the water. This interpretation is unlikely to be correct because, in this case and taking the available space into account, neither the shoulders nor the ears would be at the distance indicated in the texts:

"Perhaps it was not easy for him to obtain a glass plano-convex lens, and he used a water lens in its place. He poured a little water into the lower part of a glass globe, and upon bringing the eye so close that it touched the water, he saw that it covered a very large visual field, even receiving objects located behind his shoulders." (88)

Argentieri translates the passage as follows:
"If you take a hemisphere of glass and put your face into it, and close it well around the edge of the face, and fill it with clear water, you will see all the things that are seen from the surface of this globe, so that you will all but see behind your back" (88)

87. Keele 1955, p. 386.
88. Argentieri 1956, p. 429.

Argentieri reproduces the lower part of folio 222 recto/a with the legend "*Experiment to demonstrate vast visual field of eye – Cod. Atl. Fol. 222r-a*" (89). I have referred to the amalgamation with the extract of folio 118 verso of Manuscript K, likewise dedicated to the visual field.
Levene repeated this error but, when he compares the versions of *Keele* and *Argentieri*, he notes:

« *Keele [...] has given a different interpretation of this passage.*" (90)

and also that

"*Da Vinci was referring to the enlargement of the visual field rather than making any inference to contact lens optics.*" (91)

Brachner is also a victim of the mix-up of interpretations by *Levene*, that inspired him: he localizes erroneously the diagram of the "*artificial eye*" of folio 3 verso of Manuscript D to the Codex atlanticus and he amalgamates the citations and the diagrams of these two documents. (92)

In fact, not one of the authors cited above examined the original of folio 222 recto/a of the Codex atlanticus and has tried to understand the circumstances of the publication of these passages. This methodological hiatus has not prevented the same authors from drawing from them various conclusions and extrapolations, often unfounded, which in their turn have lead to numerous misinterpretations of the texts. (93)

It is apparent from the above that correct citations and interpretations of the texts of *Leonardo da Vinci* are extremely rare or even non-existent. The propagation of errors by their repetition in texts seems impossible to interrupt, and there is no doubt of the seriousness of this in ophthalmology, optometry and optics. We must recognize that the authors of these treatises neglect in general the publication of historical introductions and take on generally accepted ideas without submitting them to the scientific criticism required for the content of their work. Publications intended to redress such errors have had little impact. This is in keeping with the observed phenomenon that rumors and legends in today's society are often given more credence than the reality of factual information.

89. Argentieri 1956, p. 430, upper left figure.
90. Levene 1977, p. 311, note 7.
91. Levene 1977, p. 292.
92. Brachner 1988, p.21. This author makes the same error again when he attributes to the Codex atlanticus the drawing of the 'model of the artificial eye', taken from folio 3 verso of Manuscript D (Das Auge nach Leonardo. Cod. Atl. Folio 222, recto a). See also Brachner 1988, p. 22, legend and figure 12.
93. The same misinterpretation occurred in two recent doctoral theses in medicine in the first, Hoang (1984) neglected the texts of the Codex atlanticus and omitted the works of Argentieri, Levene and Strong, and, in the second, Boullaud (1987) attributed the drawing and the text of folio 222 recto/a of the Codex atlanticus to folio 8 verso of Manuscript D.

APPENDIX

Leonardo da Vinci Manuscript D

Titles and subtitles

Folio 1 recto

Title	On the eye (*dell ochio*)
Subtitle 1	Why nature did not make an equal power in the visual virtue [sense of vision] equal.
Subtitle 2	Why nature made the pupil convex, namely in relief, like part of a ball.

Folio 1 verso

Title	On the eye (*dell ochio*)
Subtitle	Why the rays of luminous bodies become larger the farther they are away from their source.

Folio 2 recto

Title	On the eye (*dell ochio*)
Subtitle 1	Whether the eidola [images] or simulacrum terminates at a point upon the eye or not.
Subtitle 2	Whether objects send to the eye their simulacra [images] with their members in the same proportion as found in themselves.
Subtitle 3	Whether the species [rays] of objects are received by the visual virtue [sense of vision] at the surface of the eye or whether they pass into it.
Subtitle 4	How the straightness of the courses of the species [rays] bends on entering the eye.

Folio 2 verso

Title	On the human eye (*dell ochio umano*)
Subtitle 1	How the species [rays] of any object, which pass through some aperture to the eye, imprint themselves on its pupil upside down, and the sense sees them upright.
Subtitle 2	How and in what way the pupil receives the simulacra [images] of the objects without intermission of the said hole.

Folio 3 recto

Title	The human eye (*ochio umano*)
Subtitle 1	How objects on the right do not appear right to the visual virtue [sense of vision] if their species do not pass trough two intersections.
Subtitle 2	Why objects diminished according to perspective appear considerably smaller than natural, even through when measured they are found to be of the same size.

Folio 3 verso

Title	The human eye (*ochio umano*)
Subtitle 1	How to perform an experience to demonstrate how the visual virtue [sense of vision] employs the instrument of the eye.
Subtitle 2	How the species [rays] give themselves to the visual virtue [sense of vision] with two crossovers by necessity.

Folio 4 recto

Title	On the human eye (*dell ochio umano*)
Subtitle	Why the mirror changes the simulacra [images] of objects from the right side to the left and the left to the right.

Folio 4 verso

Title	The eye of the human (*ochio dell omo*)

Folio 5 recto
Title On the eye of the human (*dell ochio dell omo*)

Folio 5 verso
Title On the human eye (*dell ochio umano*)
Subtitle The pupil of the eye changes instantly to various sizes according to the variation in brightness and darkness of the objects presented in front of it.

Folio 6 recto
Title On the eye of the humaen (*dell ochio dell omo*)

Folio 6 verso
Title On the human eye (*dell ochio umano*)

Folio 7 recto
Title On the eye (*dell ochio*)
Subtitle How the pupil receives the simulacra [images] of things situated before the eye only from the luce [cornea, pupillary opening] and not from the object.

Folio 7 verso
Title About the eye (*dell ochio*)
Subtitle Why an object on the right does not appear left inside the eye.

Folio 8 recto
Title The human eye (*ochio umano*)
Subtitle How the species [rays] of objects received by the eye intersect inside the albugineous humor.

Folio 8 verso
Title On the eye of the human (*dell ochio dell omo)*
Subtitle 1 Demonstrate how the eye sees behind itself the things placed in the lateral spaces.
Subtitle 2 In what way the species [rays] of the objects come to the eye.
Subtitle 3 Function of the central lines in the concourse of visible.

Folio 9 recto
Title On the human eye (*dell ochio umano*)
Subtitle 1 Why the point of the style placed across the pupil of the eye make a great shadow upon the object.
Subtitle 2 What part of the field can the eyes seen which are looking through a small hole.
Subtitle 3 Where two eyes cannot see a completely free field through a given hole.

Folio 9 verso
Title On the eye (*dell ochio*)
Subtitle 1 Why the rays of luminous bodies increase simultaneously with the space interposed between them and the eye.
Subtitle 2 Why the luminous bodies show their contours full of straight luminous rays.

Folio 10 recto
Title On eye (*de ochio*)
Subtitle 1 About the proportions of the position of simulacra [images] that imprint themselves upon the eye.
Subtitle 2 Doubts about the impression of the eidola [images] in the eye.
Subtitle 3 About the species [rays] of the objects that pass through narrow holes in a dark place.

Folio 10 verso
Title On the eye (*dell ochio*)
Subtitle 1 Conception about objects.
Subtitle 2 Of the species [rays] of the objects infused through the air.
Subtitle 3 How the eye cannot recognize the boundary of any body.