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Leonardo da Vinci, Visual Perspective and the Crystalline Sphere (lens): If only Leonardo had had a Freezer

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Summary

This study confirms Leonardo's claim to have experimented on the bovine eye to determine the internal anatomy of the eye. The experiment, as described by Leonardo, was repeated in our laboratory. The study further discusses Leonardo's primary interest in the study of the eye (especially the lens), to determine how the image of an object which enters the eye in an inverted form is righted. The study shows the evolution of Leonardo's understanding of the anatomy and the physiology of vision. Initially, in keeping with his reading of the literature, the lens was placed in the centre but he made it globular. Later he promulgated two theories, reflection from the uvea and refraction within the lens to explain reversal of the image in the eye. Subsequently he rejected the first theory and, putting credence in the second theory, experimented (1509) to show that the lens is globular and is centrally placed. The fact that the present knowledge about the lens is at variance from his findings is not because he did not carry out the experiment, as suggested by some modern authors, but because of the limitation of the techniques available to him at the time.

Résumé

Cette étude confirme l'assertion de Léonard de Vinci selon laquelle le chercheur aurait expérimenté sur l'œil de bœuf pour déterminer précisément quelle était l'anatomie interne du globe oculaire. L'expérience de Léonard a été répétée dans notre laboratoire. Dans ce travail, est ensuite discuté, l'intérêt de Léonard pour expliquer comment l'image d'un objet entrant dans l'œil, initialement inversée, est ensuite redressée. La présente étude montre encore comment évolua, au fil du temps, la compréhension qu'eut Léonard de l'anatomie et la physiologie de la vision. Initialement, fort d'une connaissance acquise grâce à ses lectures, le chercheur avait placé le cristallin au milieu de l'œil , lui conférant une forme globuleuse. Plus tard, il élabora deux théories: la première postulait une réflexion du faisceau lumineux à partir de l'uvée ; la seconde théorie voulait expliquer le renversement de l'image, dans l'œil, par une réfraction de la lumière, au sein du cristallin. Léonard abandonna ensuite sa première théorie au profit de la seconde, ses expériences de 1509 s'efforçant de démontrer que le cristallin avait une forme globuleuse et qu'il se situait au milieu du globe oculaire. Aujourd'hui, nos connaissances sur le cristallin diffèrent des conclusions de Léonard. Pourtant, contrairement à ce qu'ont suggéré certains auteurs modernes, ceci n'est pas dû au fait que Léonard ne sut pas mener à bien son expérimentation. Si le chercheur fut limité dans la réalisation de son expérience sur l'œil de bœuf, c'était parce qu'il ne disposait pas, à son époque, de la technologie nécessaire pour la faire vraiment aboutir.

Introduction

Did Leonardo da Vinci (1452-1519) base his knowledge of the eye on that of past authorities, or were his significant observations based on his own experiments? Were his theories of vision constructed solely on his readings or on his experimental knowledge? This study shows that his knowledge of ocular anatomy, the globular shape of the lens and its central location were based on his own experiments, misleading as the results were. The error was not in experimental design or observation but on technical problems that he could not have foreseen. His theories of vision were a direct corollary to his anatomical findings about the eye.

Leonardo's Quest

Why were the shape and the position of the lens within the eyeball so important to Leonardo?

Leonardo, oft described as 'Renaissance Man', went beyond the mere anatomy of the eye. His seemingly simple phrase 'sapere come vedere', 'to know how to see', knowingly or unknowingly embodied his striving to understand the anatomy and physiology of vision.

Leonardo's interest in studying vision was prompted by questions about reversion in the eye.

With his knowledge of camera obscura, Leonardo deduced that the image entering the eye was reversed in the vicinity of the pupil. The problem that he saw as a supreme challenge was 'How the species [light rays emanating from an object that is viewed] of any object, which pass through some aperture to the eye, imprint themselves on its pupil upside down, and the common sense sees them upright'.[1] How, if the image is inverted in the eyeball, does the object appear erect to us?

Leonardo's response was:'find out what re-inverts the species that intersect inside the pupil'.[2] That the brain may have some function in recording an eventual upright image was totally beyond his ken. The only option he had was to contrive a second inversion within the eyeball so that the image inverted during the passage through the pupil would be upright before falling on the end of the optic nerve.

Leonardo's *modus operandi* was quite similar to that of a present scientific project[3] firstly to review the literature, then to postulate a theory or theories, and finally to provide experimental proof. Leonardo's projects began with a study of the authorities. Next, based on his experience and probably some initial experiments, he questioned the traditional wisdom. He then postulated his own theory, rejecting views that did not conform to his experience. In the final stage he conducted experiments to gain evidence for his theory.

The anatomy of the eye, especially the location and the shape of the lens, had been variously described by Leonardo's time. Leonardo was aware that some had described the lens as being not totally globular and not located in the geometric centre. Mondino (c. 1275-1326) described the crystalline humor as' ... more towards the front ...'.[4] Ali ibn al-Abbas (c. 940-1010), in Mondino, described the le ns as a little flattened, arguing that this shape, rather than a spherical one, enabled the lens to be more securely lodged.The flattening also gave the lens a relatively larger surface area of contact with the visual rays.[5] Though Galen's (129-199) work was not illustrated, he considered the crystalline humour (lens) to be lenticular, not spherical. He thought that the slight curve of the anterior surface of the lens would help it to receive more points [of light] from the objects to be perceived.[6,7] Mediaeval writers gave the lens the same form.[8]

Leonardo's Theories of Vision

Around 1487-1490, twenty years before his experiment, Leonardo postulated that the lens was in the centre of the eye and was globular (fig. I). The position and the shape of the lens were important to Leonardo. He had previously suggested that the lens magnified an image'like a ball of glass full of water'.[9] He now combined the function of the glass ball with that of the camera obscura.The converging rays from an object *cross* at the pupil and the inverted image is then reverted in the lens (the glass ball) and falls on the optic nerve.[10] Based on this knowledge, Leonardo proposed two theories of vision for producing the second inversion, or reversion; I), reflection from the uvea (the uvea theory); 2), refraction within the lens.

I) Reflection from the uvea. Leonardo considered the uvea to be a spherical concave mirror. Rays of the inverted image pass either through the crystalline sphere or bypass the sphere and fall directly on the uvea. Using the laws of reflection, Leonardo suggested that the inverted image is then reflected from the uvea onto the posterior surface of the lens,[11] (fig. 2).

Leonardo later rejected the idea of reflection from the uvea based on the principle that '... the angle of incidence must be equal to the angle of reflection'.[12] From this basic principle of the physics of light he deduced that it is impossible for the uvea to reflect the incident rays onto the crystalline sphere or to the termination of the optic nerve in the sphere. Ultimately he doubted that rays could be reflected off the inner black surface of the uvea.[13] 'The pupil is black because the uvea is black ...'.[14] His knowledge of the colour of the uvea is additional argument that he must have dissected the eye.

2) Refraction within the lens. Though the camera obscura was first described by Al-Kindi and Alhazen,[15] Leonardo was the first to conceive of the eye as a camera obscura and illustrate the principle.[16] He demonstrated, like Alhazen, that rays travel in straight lines and continue to travel on that path even after an intersection.[17] He was aware that because of the crossing of the rays at the spiracolo (the pupil) of the eye, the image entering the eyeball would be smaller and inverted. He attempted to solve the enigma of an inverted vision. 'Necessity has provided that all the images of objects in front of the eye shall intersect in two places. One of these intersections is in the pupil, the other in the crystalline lens; ...',[18] (fig. 3).

Refraction of the rays in the eye, known at least since Archimedes (287-212 B.C.), was common knowledge in the field of optics in the west from about the thirteenth century.[19] Leonardo wrote'... it is necessary that the line should be bent as it is changed from the rarity of the air to the density of the humours of the eye'.[20] He used this knowledge of intersection and refraction in a modified hypothesis to revert the image falling on the optic nerve, (fig. 4).The image, inverted at the pupil, falls on the front of the lens. The rays are refracted and pass through the lens, without intersection, to the posterior surface of the lens.As the rays exit, there is a second refraction and the rays intersect a second time (reverting the image) before reaching the optic nerve.

The shift from refraction within the lens to refraction on the posterior surface of the lens was prompted by the location of the termination of the optic nerve. In fig. 3 (c. 1492), the optic nerve terminates in contact with the posterior surface of the lens. In fig. 4, more likely of a date closer to 1500, the optic nerve terminates at the periphery of the eyeball. Having postulated his theory, Leonardo now proceeded to his experiment to determine ocular anatomy. He believed in experimental inference. 'Trust only those who have exercised their minds not on the proofs of nature but on the results of their own experiments'.[21]

The Experiment

In 1509 Leonardo described an experiment to study the position of the lens in the bovine eye.'In the anatomy of the eye, in order to see the inside well without spilling its humour, one should place the whole eye in white of an egg, make it boil and become solid, cutting the egg and the eye transversely in order that none of the middle portion of the eye be poured out'.[22] Leonardo, in mentioning sectioning the eyeball 'transversely', meant exactly what is understood today as a transverse section, the modality in which the body is viewed in a MRI or a CAT scan. His illustrated work is replete with sketches of skulls, brains, eyes and even an upper leg in transverse sections.

This experiment was proposed a few years after he made wax casts of the ventricles of the brain (1504) in his quest to find the 'senso commune' - the area in the brain where sensory input is interpreted.[23] Some medical historians have doubted the execution of this experiment and have looked askance at Leonardo as evident from their quotes. 'Had Leonardo used this technique [sectioning of the eyeball] successfully, it is unlikely that he would have persisted in drawing the lens as round and central'.[24] 'Notwithstanding Leonardo's suggestion of a method of preserving the relations of its parts during dissection, his figures give no evidence that he had made use of the method'.[25]

Belt attributes the central placement of the lens to the arrangement found in the myopic ox, an animal Leonardo used. Belt further elaborates that during the cutting of the eyeball '...the hard lens, which was difficult to cut, invariably slipped from its proper location...'[26] Veterinary anatomy texts will refute this statement,[27] and so does the experiment conducted for the present study.'... in the anatomy of the dead, it [lens] is usually separate'.[28] This separation is not found in our observation of more than two thousand eyeballs bisected in the human gross anatomy laboratory. If Leonardo was capable of undertaking the experiment on the ventricles, there is little reason to doubt that he would carry out a much simpler experiment showing the internal anatomy of the eye.

Experimental Evidence

For this study, an experiment following Leonardo's instructions was performed on a bovine eye. The bovine eyeball was placed in a staining dish, routinely used for staining histological slides. The dish was 9.5 cm in length, 7.5 cm wide and 6.0 cm high. Initially, egg white was placed in the dish to the depth of one centimetre and heated till it congealed and became white in colour. This was to serve as the base on which to place the eyeball. The latter was centrally placed on its side, with its long axis corresponding with the long axis of the dish. The superior and the inferior surface of the eyeball faced the longitudinal walls of the dish. The eyeball was then totally submerged in egg white. Subsequently, the dish was placed in a water bath and heated till the egg white congealed. On cooling, the block was removed from the dish. Leonardo does not mention the type of instrument he used for sectioning the eyeball. From a sketchy illustration in Ms K I 19r[29] it appears to be some form of a scalpel. In our experiment the block and the eyeball was sectioned, longitudinally and in the midline, with a brain knife. The length of the brain knife allowed a smooth cut without the 'sawing' action by a shorter scalpel blade, which may result in distortion of the specimen. In the cut transverse section, the lens was found to be globular and in the centre of the eyeball (fig. 5), as Leonardo has depicted in his illustrations. The spherical shape of the lens can be attributed to swelling of the alpha and beta crystalline protein, which is 80 to 90 percent of the protein in the lens[30]. The swelling of the lens caused it to break free of the zonular fibres of the ciliary body and move to the centre of the eye.

The other eyeball from the same animal was frozen and then sectioned in a similar plane with a brain knife. This section revealed the lens to be elliptical and located anteriorly in the eye, as seen in the current works on ocular anatomy. The heating process resulted in some shrinkage of the eyeball. The ratio of the frozen to the boiled eyeball was 1.28:1.

Our experiment leaves no doubt that Leonardo did section the eyeball to determine the shape and position of the lens. He used basically the same method current in routine histological procedure. Instead of liquid paraffin, Leonardo used egg white and subsequently boiled the whole preparation to obtain a block suitable for sectioning.

Why did Leonardo use egg white, instead of wax that he used previously in studying the ventricles of the brain? His intention, stated above, was to section the eyeball without displacing its contents. Immersing the eyeball in hot wax and allowing the wax to cool would not have sufficiently solidified the inside of the eyeball to allow sectioning without the humors running out. Leonardo's decision to use the embedding medium was more likely substantiated by his observation of a cooked egg. The redness or yolk of the egg remains in the centre of the albumen without sinking on either side'.[31] Had Leonardo chosen to freeze the eyeball, possibly by putting it on the window-sill in winter, his findings would have been more likely to be anatomically correct.

Leonardo's Findings

After his experiment, Leonardo wrote of his awareness of the disparity between his experimental knowledge and those of his predecessors 'The eye, whose function we certainly know by experience, has down to my own time, been defined by an infinite number of authors as one thing; but I find, by experience that it is quite another'.[32] Based on his experiments, Leonardo believed that the eye consisted of two concentric circles, the outer layer of uvea filled with albuminous or gelatinous material with the cornea in front. Located in the centre was the inner spherical vitreous body or the crystalline sphere - the lens.[33] Leonardo admonished 'Describe in your anatomy what ratios exist between the diameters of all the spheres of the eye and what distance there is between them and the crystalline sphere'[34]. He was aware that others had not described the lens as totally globular and not located in the geometric centre.

Leonardo's visual theories are not considered valid by present day historians. 'But in the end he failed to formulate a valid optical theory'.[35] Valid by what standards, however? Validity is, and should be, judged on the basis of prevalent knowledge and technique. Considering the state of both at the time and Leonardo's knowledge, experimental and textual, his theory of vision was as valid as any hypothesis in science.

References

Translations from Leonardo's manuscripts were taken mainly from various secondary sources. In the footnotes, where applicable, the *secondary source* is followed by the primary source of Leonardo's writings in bold print. Listed below are the abbreviations used in the footnotes and the full title with the dates.

MS A. 1492; MS B. 1490; MS D. 1508; MS E. 1513-1514; MS I. 1497; MS K. 1504. Manuscripts in the library of the Institut de France, Paris.

B.M.Arundel MS in the British Museum. 1504, 1508, 1516.

B.L British Library, London, 1504-1507.

C.A. Codex Atlanticus, Ambrosian Library, Milan.

W.L. MS at the Windsor Library. 1490-1516.

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Figure Legends

Fig. I. Leonardo da Vinci. Diagrammatic sagittal section of the head. The lens is globular and in the centre of the eyeball. Compared to the longitudinal section of an onion. Windsor I2603r. c. 1490. Copied from O'Malley CD and Saunders JB: Leonardo da Vinci on the Human Body. New York, Henry Schuman, 1952. fig. 142

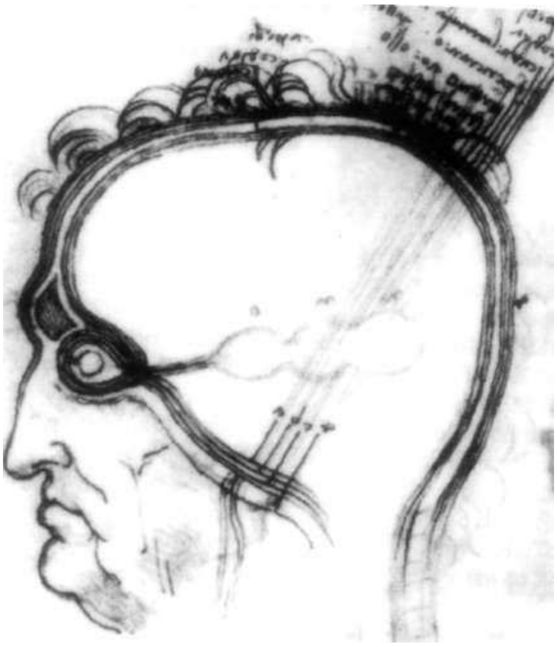
The following three figures copied from MS D can be traced back to the I490's either through Leonardo's earlier manuscripts or Codex Atlanticus. The dates quoted are close estimations. (See Strong 1979, pp. 329-331).

Fig. 2. Leonardo da Vinci. Inverted rays from the pupil go to the uvea where they are reverted and reflected back into the lens upright. (MS D 7v). c. 1492. Copied from Strong, fig. 33, p. 74.

Fig. 3. Leonardo da Vinci. Two mechanisms, reflection and refraction, for inverting the rays that intersect inside the pupil. (MS D I Or), c. 1492. Copied from Strong, fig. 57, p. 89.

Fig. 4. Leonardo da Vinci. 'Double intersection of rays, outside the lens, so as to fall on the optic nerve in an upright position.' (MS D 3v). c. 1492-1500. Copied from Strong, fig. 20, p. 56.

Fig. 5. Hemi-section of the two eyeballs of the same bovine. Left, prepared according to Leonardo's instructions. Note the central position and the globular appearance of the lens. Right, section of the frozen eyeball. The lens is elliptical and in the normal anatomical position.



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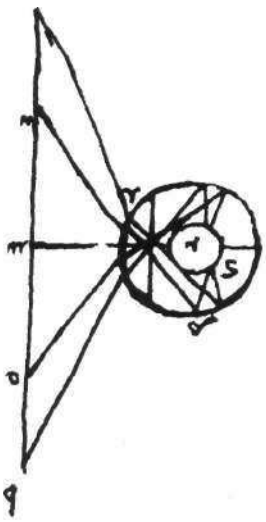

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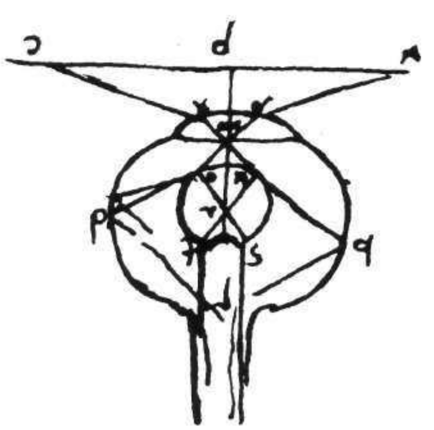

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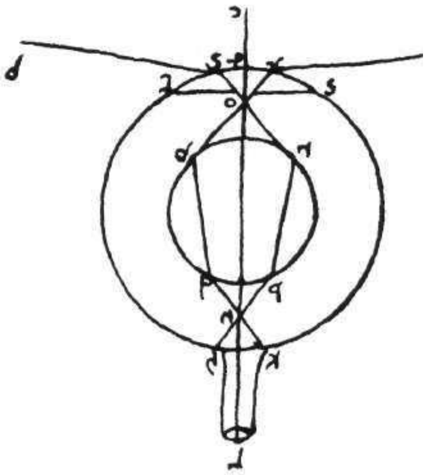

Fig. 4

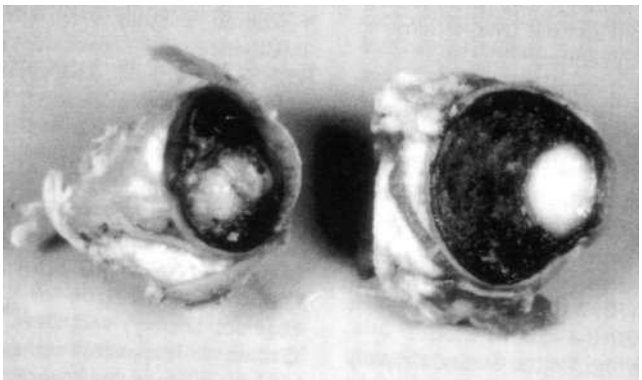

Fig. 5