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The Art of the Science of Renaissance Painting

David Hockney
7508 Santa Monica Blvd., Los Angeles, CA 90046-6407

Charles M. Falco
Optical Sciences Center, University of Arizona, Tucson AZ 85721-0077
falco@u.arizona.edu

Abstract: One of us (DH) observed an almost "photographic" quality in certain drawings and paintings from as early as the Renaissance that led him to make an extensive visual investigation of western art of the past 1000 years. The result of this investigation was the revolutionary claim that artists even of the prominence of van Eyck and Bellini must have used optical aids. However, many art historians insisted there was no supporting evidence for such a remarkable assertion. This paper discusses some of the optical evidence we subsequently discovered that convincingly demonstrates optical instruments were in use by artists as early as c1425, nearly 200 years earlier than widely thought possible. This discovery that optics had been used to project images coincides with the remarkable transformation in the reality of portraits that occurred early in the 15th century.

I. Introduction

One of us (DH) recently observed certain qualities in the portraits of Jean-Auguste-Dominique Ingres that suggested the artist had used some sort of optical instrument as an aid.[1] This observation developed into an extensive visual investigation of a large number of European paintings of the past 1000 years to determine whether this quality appeared in earlier work. The results of this investigation are presented in detail elsewhere along with a discussion of its significance for an understanding of the art of the past 600 years.[2]

During this study we began to examine paintings for the presence of optical artifacts that could serve as supporting scientific evidence for these visual observations. Here we briefly describe some of the scientific evidence contained within three paintings that demonstrate lenses were in use by certain artists to project images as early as c1425. We present only a general discussion here, and refer interested readers to previous publications for details.[2,3,4]

II. The Projection of Images by Concave Mirrors and Refractive Lenses

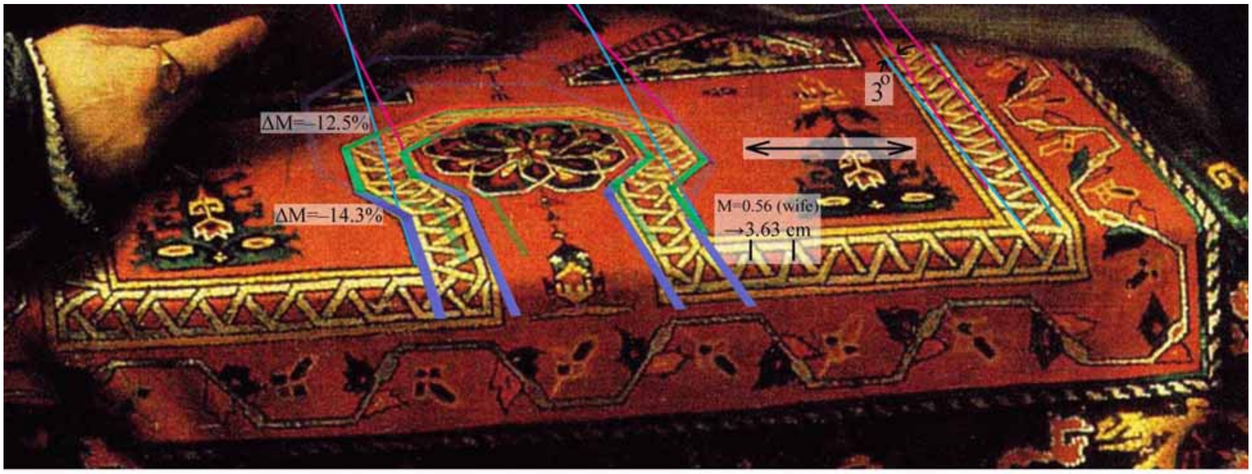
Few non-scientists are aware that concave mirrors can be used to project images. Historians unaware of this optical property might not realize that a "mirror" listed in an inventory of an artist's possessions could be a concave one, in which case it might have been used by the artist to project images. Since we have discovered a variety of circumstantial evidence that suggests such concave mirrors were used by at least some artists, we note here that a concave spherical (or parabolic) mirror can function as a "mirror lens." Refractive lenses also can be used to project images, of course. However, images projected by concave mirrors have the advantage that, because a mirror reverses right and left, the symmetry of the image projected by a concave mirror is identical to that of the original subject. The advantages of this for an artist creating an image are discussed elsewhere.[2]

III. Examples of Optical Artifacts in Renaissance Paintings

A. *Husband and Wife*, Lorenzo Lotto, c1523–4

Figure 1 is a detail from this painting, showing an octagonal pattern on a table covering that appears to go out of focus at some depth into the painting. Beneath the painting is a summary of the qualitative and quantitative evidence we have extracted from it, showing that the features within the painting are fit to better than 1% by calculations from the laws of geometrical optics.

The most important qualitative feature exhibited by this painting is the way the image in the octagonal portion of the painting seems to go out of focus as it recedes into the distance. Although a simple lens can be focused at only one specific distance at a time, the brain causes the muscles of a human eye to quickly and automatically alter the shape to refocus to different depths as the eye traverses a scene. Because of this, we do not simultaneously see part of a scene in focus and part out of focus. In contrast with the eye, no matter



Summary of Optical Evidence that Lorenzo Lotto Used a Lens in c.1523

Qualitative

- Octagonal pattern goes out of focus
- Two vanishing points are readily apparent in the octagonal pattern
- Excellent fit of a perspective-corrected octagon to the pattern
- Change to a 2nd vanishing point in the border is apparent at same depth into scene as octagonal pattern goes out of focus

Quantitative

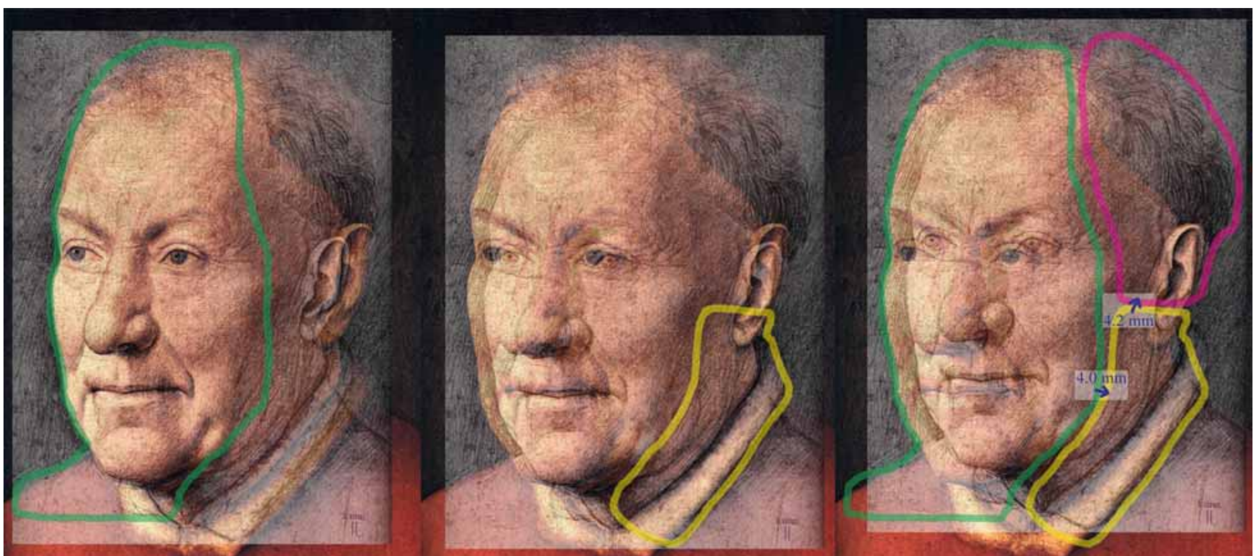
- Focal length of lens calculated as 53.8 cm (from ***magnification*** of painting)
- Diameter of lens calculated as ~2½ cm (from ***depth of field***)
- Magnification decrease of –14.3% calculated where perspective of octagon initially changes (from ***depth of field + focal length***)
- Second magnification decrease of –12.5% calculated where perspective of octagon changes (from ***depth of field + focal length***)
- Change in convergence of 3° calculated for the border pattern (from ***change in magnification upon refocusing + focal length***)

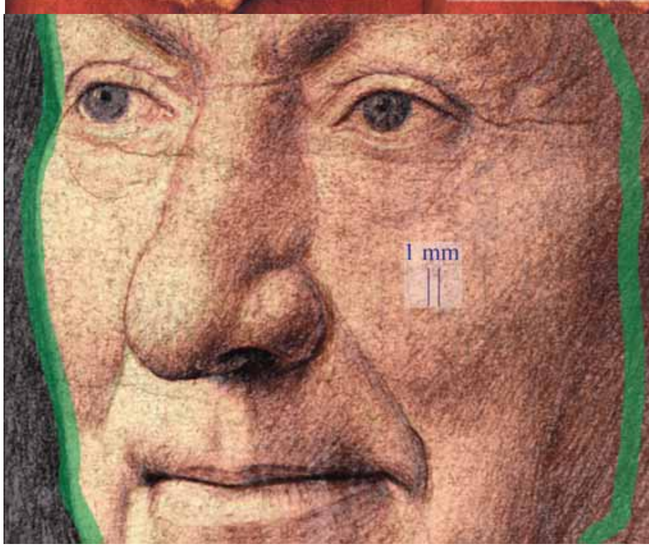
what the distance of focus of a simple lens, only a certain field on either side of that distance will remain acceptably sharp, resulting in a depth of field that depends on the focal length and diameter of the lens. To change that distance of focus requires physically altering the position of the lens with respect to the subject and the image plane. Refocusing a lens to a depth further into a scene from its original plane of focus requires moving the lens closer to the image plane (and *vice versa*). Moving the lens closer to the image plane results in a small decrease in the magnification of the projected scene, as well as in a slight change in the vanishing point, since the lens is now at a slightly different position. While both of these effects are quite small for magnifications M<<1, which is the magnification range for most ordinary photographs, they increase in magnitude as M increases (for example, the image of a 1.6 m woman will be ~2 cm tall when projected onto a piece of film or a CCD sensor, so M . 0.012, whereas the woman in the Lotto painting discussed here is at M . 0.56, which is nearly 50× greater magnification). Although such effects are fundamental characteristics of images projected by lenses, they are extremely unlikely to occur in paintings produced by eye alone.

To summarize, from the measured magnification of this painting (0.56) determined from the size of the woman in it, geometrical optics dictates that if Lotto used a lens to project the octagonal pattern there must be three regions corresponding to the depths into the scene where he would have been forced to refocus, with three different magnifications, and hence three sets of vanishing points. All of these complex features are found in the painting, and all are in excellent quantitative agreement with the predictions of geometrical optics. This provides extremely strong evidence indeed that Lotto used a lens to aid him in creating this detailed portion of this painting. Further, the focal length of the lens as well as the distances from the lens to the table covering as well as to Lotto's canvas are all quite reasonable, allowing significant insights into the actual layout of the artist's studio.

b. *Cardinal Albergati*, Jan van Eyck, c1432

Van Eyck's drawing of Cardinal Albergati is ~40% smaller than his painting. However, when we enlarge the drawing and overlay it on the painting, the correspondence between the major features (eyes, nose, mouth, etc.) as well as the minor details (wrinkles, lines, creases, etc.) within each of the three large regions outlined above is to a precision of better than 1 mm, providing strong evidence that van Eyck used a lens as a tool. The Cardinal visited Bruges for four days, 8–11 December 1431, when the daylight in northern Europe is at its lowest. Since the brightness of a projected image scales as the square of the magnification, this ~40% reduction in size of the drawing would have resulted in an image ~2× as bright for van Eyck to work with. Later, when the grey skies and dim light of winter were gone, the same lens and optical setup could be used to enlarge the drawing to the size that the Cardinal presumably had commissioned for the painting. To do this, the drawing would have been placed in the sunlight, rather than the Cardinal, and its enlarged image projected onto the canvas in the identical fashion used to produce the drawing in the first place. The three





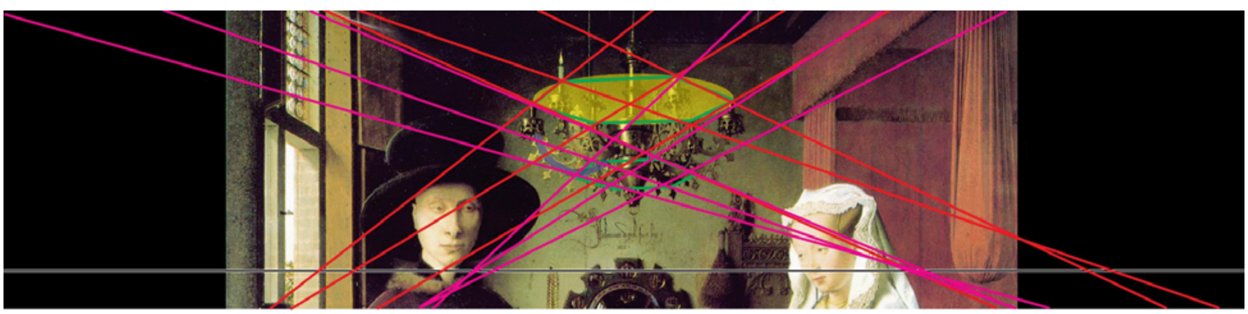
major regions on the canvas are accounted for by two very slight "bumps" of the optical setup during this process of producing the enlarged painting. The lengths and directions of the arrows are drawn to scale in the above figure, with the neck and ear lobe region 4.0 mm to the right and slightly down from the main portion of the face, and the upper ear and hair region 4.2 mm up and to the right from there.

c. *Arnolfini Marriage,* Jan van Eyck, 1434

The perspective, texture, and detail of the complex chandelier in this painting are all quite remarkable, which lead us to examine it for evidence that it might be based on an optical projection. The elementary rules of perspective seemingly dictate that lines drawn through common elements of an optical projection should meet at well defined foci, all of which must be on a single horizon line. However, any real object, such as a chandelier, inevitably will deviate from absolutely perfect hexagonal symmetry. While this should be obvious, the consequence of even very small variations is that vanishing points will not obey the simplified laws of perspective as taught in most textbooks.[5]

Comparing the measured height of an actual candle flame, 3.9 cm, to the one van Eyck included in the painting provides a size scale for this chandelier. With this value, the overall width of the chandelier between opposite candle holders is 96.7 cm, and the magnification is 0.16. This magnification is small enough that the depth of field for a lens falling within any reasonable range of focal lengths would be over 1 m, and hence the entire image could have been captured without refocusing. This would have made the task simpler for the artist and, indeed, makes analyzing the image easier than if it had been composed of several segments.

After correcting for perspective to convert the chandelier to a plan view, we find the maximum deviation of any of the candle holders from a perfect hexagon is only 7^{o}, which in turn corresponds to the end of this arm being only 6.6 cm away from its "ideal" hexagonal position. The root-mean-square deviation of all six candle holders from perfect hexagonal symmetry is only 4.2^{o}, or 4.1 cm. While there is no reason to expect a real 15th century chandelier to have been made to an accuracy any greater than this in the first place, there is also the possibility some or all of the individual deviations could have resulted from slight bends during transportation, hanging, or cleaning. A circle through the perspective-corrected positions of the candle holders shows the radial positions of each are identical to within a worst case of only 7.4 mm; i.e., only 1.5% of the radius of the chandelier.



Summary of Evidence the Chandelier is Based on an Optical Projection

- The length, width, and shape of the main arc of all 6 arms are identical to within ~2%;
- Radii of all 6 candle holders are within ±1.5% of the radius of a perfect circle centered on the axis of the chandelier;
- Angular positions of all 6 candle holders are within $\pm 4^{o}$ of the points of a perfect hexagon;
- To within ±1 mm, the positions of the lowest points on the arcs of 5 of the 6 arms have the identical perspective-corrected hexagonal symmetry as the candle holders;
- Vanishing points defined by the candle holders and by the arcs converge to the same horizon to within the accuracy expected for the imperfections in a real chandelier;
- Qualitative: The overall size of ~1 m estimated from the flame is physically reasonable, as are the measured minor variations in lengths and angles for such an ornate, hand-made object (although not discussed here, van Eyck did deviate from "perfect" optical perspective in certain details).

IV. Summary and Conclusions

The three paintings we have briefly described in this manuscript contain optical evidence showing that lenses were in use for projecting images nearly 200 years earlier than previously even thought possible, and account for the remarkable transformation of the reality of portraits that occurred early in the 15th century. We emphasize that the evidence in these paintings, and all the others we have analyzed, shows that *some* features of *some* paintings were produced with the aid of lenses. Useful as it is as a tool, a lens does not arrange a composition, fill in the colors or shadings, or make any of the many other artistic decisions that are needed to create a painting. More information on optical aspects of this topic can be found at:

http://www.optics.arizona.edu/ssd/FAQ.html

V. Acknowledgments

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VI. References

1. Lawrence Weschler, "The Looking Glass," *The New Yorker,* 64–75 (31 January 2000).

2. David Hockney, *Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters* (Thames & Hudson, London, 2001).

3. David Hockney and Charles M. Falco, "Optical Insights into Renaissance Art," *Optics and Photonics News* 11, 52 (July 2000).

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

5. See, for example, Marilyn Stokstad, David Cateforis and Stephen Addis, *Art History*, 2nd Edition (Prentice-Hall, New York, 2002).