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Optics at the Dawn of the Renaissance

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Abstract: Recently, one of us (DH) observed that certain drawings and paintings from as early as the Renaissance seemed almost "photographic" in detail. An extensive visual investigation of western art of the past 1000 years resulted in the revolutionary claim that artists even of the prominence of van Eyck and Bellini must have used optical aids. However, art historians insisted there was no supporting evidence for such a remarkable assertion. This paper presents some of the optical evidence we subsequently discovered that convincingly demonstrates optical instruments were in use—by artists, not scientists—nearly 200 years earlier than widely thought possible, and that accounts for the remarkable transformation in the reality of portraits that occurred early in the 15th century.

OCIS codes:(000.2850) History and philosophy; (000.2060) Education; (100.2960) Image analysis; (100.5010) Pattern recognition and feature extraction

1. Introduction

This paper describes a novel application of known optical principles to an unusual problem, that of analyzing paintings produced as early as the Renaissance to look for evidence of the use of optical devices. The results of our work show that certain artists as early as c. 1425 used optical projections as aids for producing some elements of their paintings. The discoveries discussed in this paper demonstrate that optical instruments were in use by artists nearly 200 years earlier than commonly thought possible, and account for the remarkable transformation in the reality of portraits that occurred early in the 15th century.

As described elsewhere [1], at a recent exhibition one of us (DH) observed certain qualities in the portraits of Jean-Auguste-Dominique Ingres that suggested to him the artist had used some sort of optical instrument as an aid. This observation of a "photographic quality" in the Ingres portraits 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 the work of earlier artists. Briefly, we have now traced this photographic quality as far back as the early fifteenth century. The results of this visual 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 the course of this study we became interested in the possibility that optical artifacts might exist within the images of some paintings that could serve as supporting scientific evidence for these visual observations. Certain optical artifacts had been previously identified in some of Vermeer's work in the seventeenth century [3][4][5]. However, it clearly would be of major significance if evidence could be found for use of any optical instrument that pre-dated Girolamo Cardamo's 1550 description of a *camera obscura* that incorporated a lens [6]. In the present manuscript we discuss some of the scientific evidence in three paintings that demonstrate lenses were in use by certain artists to project images as early as c. 1425.

We presented our initial scientific results in a previous paper [7]. In that paper we concentrated on a remarkable painting by Lorenzo Lotto from c. 1533–4 that actually contains enough information within it to allow us to calculate such details as the approximate focal length and diameter of the lens Lotto used. Having now established visually [2] as well as scientifically [7] that lenses were used by certain Renaissance artists, this discovery has a number of implications for both the history of science as well as the history of art. In this paper we present additional results from our analysis of three paintings. While we include brief discussions of the physical principles behind several optical artifacts, the reader interested in additional details of the underlying optical principles is referred elsewhere [8].

2. The Imaging Properties of Concave Mirrors and Refractive Lenses

In the course of our work we discovered that few non-scientists are aware that concave mirrors can be used to project images. This is particularly important for several reasons. First, historians unaware of this optical property might erroneously assume that even when a "mirror" is listed in an inventory of an artist's possessions, the absence of a "lens" from the inventory means the artist could not have projected an image. Second, the image projected by a concave mirror gives it one important advantage over that projected by a refractive lens for an artist creating a painting. Since we have discovered a variety of circumstantial evidence that points to the use of such concave mirrors by at least some artists, we explicitly note here that a concave spherical (or parabolic) mirror can function as a "mirror lens." While both refractive lenses and concave mirrors can be used to project images, those from the latter 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].

Typically, we have found that paintings containing evidence of one optical artifact often contain evidence of others as well. However, length limitations of the present paper make it impossible to analyze a number of paintings in detail, so we have limited ourselves to three early examples here. However, these examples alone provide convincing scientific evidence that lenses were used by artists as early as c. 1425.

3. Application of Geometrical Optics to Analyze Renaissance Paintings

a. Lorenzo Lotto's *Husband and Wife*, c. 1523–4

Analysis of this painting shows how an understanding of geometrical optics and perspective provides a powerful way to show certain images were created with the aid of lenses, as well as to extract quantitative information from those images. Figure 1 is a detail from Lorenzo Lotto's *Husband and Wife* of c. 1523–4, showing an octagonal pattern on a table covering that appears to go out of focus at some depth into the painting. Overlaid on the painting are three segments of a perspective-corrected octagon whose details we calculate below. Although there are several features of interest in Lotto's *Husband and Wife*, here we are concerned only with the way the image in this portion of the painting seems to go out of focus as it recedes into the distance.

While 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 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 (note that the image of a 1.6 m woman will be ~2 cm tall when projected on a piece of film or a CCD sensor, so M . 0.012, whereas the woman in the Lotto painting discussed below is at M . 0.56, which is nearly 50× greater magnification). Such effects are fundamental characteristics of images projected by lenses, and are extremely unlikely to occur in a painting if an artist had instead laid out patterns following geometrical rules first articulated in the fifteenth century [9].

Although we discussed several aspects of this painting elsewhere [2,7], here we provide additional details of our analysis. As we showed in Ref. 7, the width of the wife's shoulders in the painting provides an internal length scale that lets us determine the magnification to be M . 0.56, and from this we determine the depth of field to be 16±1.5 cm. From geometrical optics the focal length (FL) and magnification (M) are given by:

$$1/FL = 1/(d_{lens-subject}) + 1/(d_{lens-image}) \tag{1}$$

and

$$M = (d_{lens-image})/(d_{lens-subject}) \tag{2}$$

As indicated by the colored segments on Figure 1, there are three regions of this octagonal pattern resulting from Lotto refocusing twice as he exceeded the depth of field of his lens. We label these Regions 1, 2, and 3, with Region 1 the closest to the front of the painting (blue, in Fig. 1). Thus, for the first two Regions,

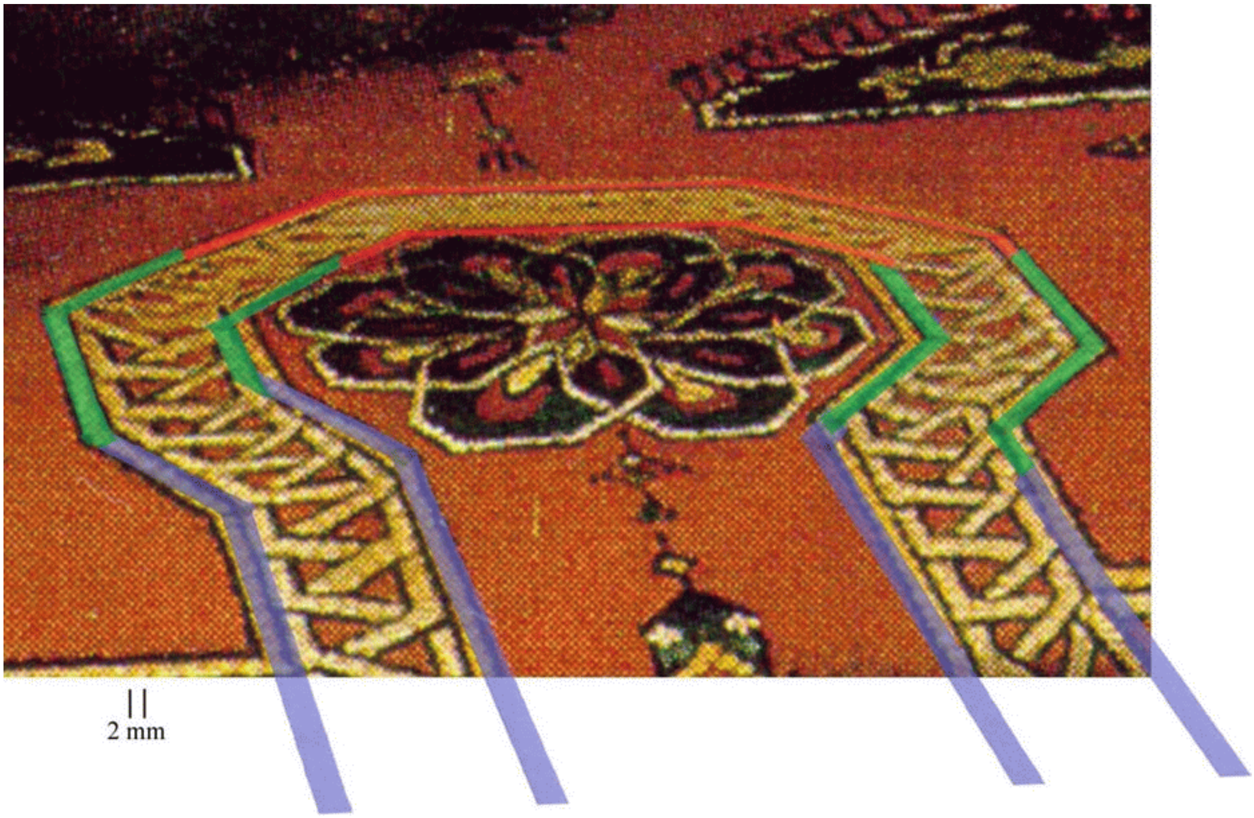

Fig. 1. Detail of *Husband and Wife*. The blue, green, and red overlays are perspective-corrected sections of an octagonal pattern fit to the painting. If this portion of the painting is based on a projected image of an actual table covering, Lorenzo Lotto would have painted the front (blue) section, then moved his lens to refocus further back when the depth of field had been exceeded and continued to paint the center (green) section, then refocused one more time to finish the final (red) portion. As can be seen, the details of the painting are in excellent qualitative agreement with the three-segment, perspective-corrected octagon predicted by the laws of geometrical optics for such a projected image. As described in the text, the details are in excellent quantitative agreement as well.

$$1/FL = 1/(d_{lens\text{–}subject1}) + 1/(d_{lens\text{–}image1}) \qquad (3)$$

and

$$1/FL = 1/(d_{lens\text{–}subject2}) + 1/(d_{lens\text{–}image2}) \qquad (4)$$

However, as we showed in Ref. 7, the measured depth of field is 16 cm, so for Region 2

$$d_{lens\text{–}subject2} \;.\; d_{lens\text{–}subject1} + 16\text{ cm} \qquad (5)$$

and

$$1/FL = 1/(d_{lens\text{–}subject1} + 16\text{ cm}) + 1/(d_{lens\text{–}image2}) \qquad (6)$$

Because Region 2 is further into the scene, and therefore at slightly lower magnification, than is Region 1, its depth of field will be somewhat larger than 16 cm. However, for the purposes of this paper we will omit this complexity. Thus, Region 3 of the pattern starts at a depth of approximately 2×16 cm = 32 cm into the scene, so

$$d_{lens\text{–}subject3} \;.\; d_{lens\text{–}subject1} + 32 \text{ cm} \tag{7}$$

and

$$1/FL \;.\; 1/(d_{lens\text{–}subject1} + 32 \text{ cm}) + 1/(d_{lens\text{–}image3}) \tag{8}$$

The fit of the three segments of the perspective-corrected octagon overlaid on Figure 1 allows us to determine the relative magnifications M of the three regions as 0.56, 0.48, and 0.42, respectively, from which we obtain:

$$0.56 = d_{lens\text{–}image1} \,/\, d_{lens\text{–}subject1} \tag{9}$$
$$0.48 = d_{lens\text{–}image2} \,/\, (d_{lens\text{–}subject1} + 16 \text{ cm}) \tag{10}$$
$$0.42 \;.\; d_{lens\text{–}image3} \,/\, (d_{lens\text{–}subject1} + 32 \text{ cm}) \tag{11}$$

Thus, we have six equations (3, 6, 8, 9, 10 and 11), but only five unknowns: FL, $d_{lens\text{–}subject1}$, and $d_{lens\text{–}image1,2,3}$. Solving these equations uniquely determines:

$$\begin{aligned} \text{focal length (FL)} &= 53.8 \text{ cm} \\ d_{lens\text{–}subject1} &= 149.8 \text{ cm} \\ d_{lens\text{–}image1} &= 83.9 \text{ cm} \end{aligned}$$

Note that there are no adjustable parameters in our analysis of this image. In going from Region 1 to Region 2 the magnification, as measured from our fit of a perspective-corrected octagon, decreases by 14.5% from the original 0.56 of the painting, in excellent agreement with the 14.3% we calculate from the above equations. Similarly, the measured magnification decreases by a further 12.3% when going to Region 3, again in excellent agreement with the calculated value of 12.5%.

To summarize, using the measured size of the woman in this painting as the only input parameter, 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, providing extremely strong evidence indeed that a lens was used. 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. Robert Campin's *Merode Triptych*, c. 1425–28

The earliest optical evidence we have found to date is in the center and right panels of Robert Campin's *Merode Triptych* of c. 1425–28, a detail of which is reproduced in Figure 2. This detail exhibits the same complex change in perspective resulting from having refocused a lens as discussed above for Lorenzo Lotto's *Husband and Wife*. Overlaid on this painting are three segments of an ideal perspective-corrected lattice that fit the painting to an accuracy of better than 1 mm. Not shown is that a single-segment ideal lattice cannot be made to fit. As can be seen, the latticework in the seat back contains unmistakable evidence of two small changes in perspective that occur at depths into the scene where a lens would have had to have been refocused. A similar change in the perspective at roughly the same depth into the scene also is in the latticework of the seat back in the central panel of this triptych. The complex perspective exhibited by the latticework is an inevitable outcome from the depth of field of a lens, but would be very difficult (and extremely unlikely) to be reproduced by any geometrical technique.

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

The perspective, texture, and detail of the complex chandelier in this painting are all quite remarkable, leading us to examine it for evidence that it might be based on an optical projection. The elementary rules of perspective (see, for example, Fig. 24 of Reference 9) seemingly dictate that lines drawn through common elements of an optical projection

Fig. 2. Detail of right panel of the *Merode Triptych*. The blue, green and red overlays are perspective-corrected sections of the same ideal latticework, revealing where Campin had to refocus his lens when he exceeded its depth of field.

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 [10]. This is shown on the bottom of Figure 3, where lines accurately drawn through corresponding features on a photograph of a light fixture show marked deviation from optical perspective as it is described in elementary textbooks. Interestingly, the top of this figure shows that lines carefully drawn through corresponding features on van Eyck's chandelier (the tops of the six candle holders) show similar deviations. Although this might seem an obvious test to conduct on an image, as can be seen from these examples, drawing lines on the image of this chandelier is too simplistic an approach to reveal anything useful.

Another important point is that any painting of a three-dimensional object has reduced that object to a two-dimensional space, so some spatial information inevitably has been lost. This is unlike the cases discussed earlier of the Lotto and the Campin paintings, where the carpet and seat back both were two-dimensional. Finally, we note that the decorative elements on the top and bottom of each of the six chandelier arms on this painting obviously would have been attached individually (by soldering or riveting) in fabricating such a complex piece from metal. This easily can be seen by examining a detail of the chandelier arms, as shown in Figure 4. Because of this, the placement of these decorative elements will vary from arm-to-arm, thus making them completely unsuitable for any kind of perspective analysis. For all of these reasons, it is important to analyze appropriate aspects of the chandelier in the painting in order to determine whether or not it was based on an optical projection.

We first need to establish the approximate magnification of the chandelier, since the depth of field of a projected

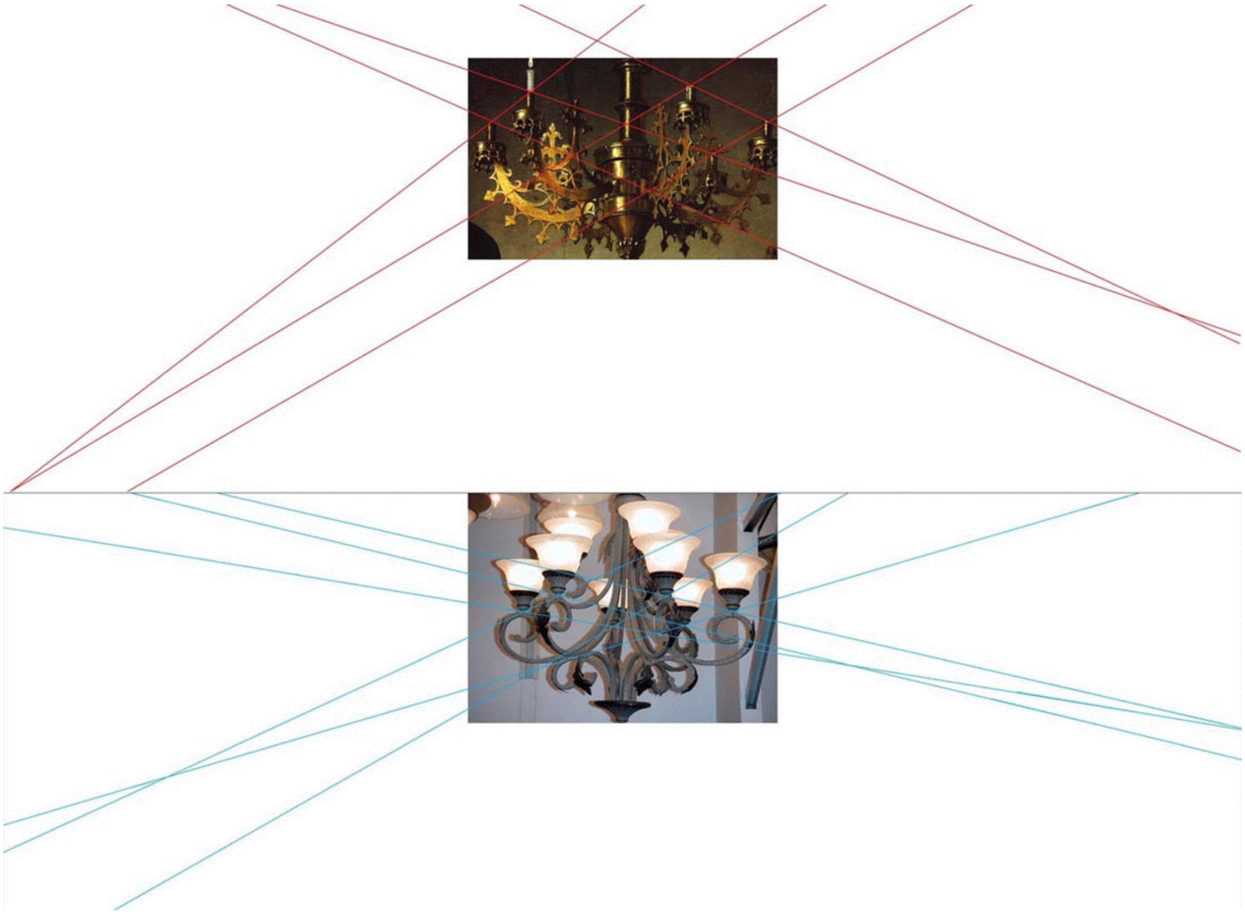

Fig. 3. (top) Chandelier in the *Arnolfini Marriage*. Lines accurately drawn through the tops of the corresponding six candle holders do not meet at foci on a horizon line as seemingly dictated by the simplified laws of perspective. **(bottom)** Photograph of a light fixture. Lines accurately drawn through the corresponding six bulb holders show deviations that are remarkably similar to those of the chandelier. In this case there is no doubt whatever the image is based on an optical projection, showing that even slight deviations from defect-free, perfect hexagonal symmetry are sufficient to make inapplicable the simplified laws of perspective.

image depends on this parameter, and in turn establishes whether or not a lens could have captured the entire image without the magnification-change effects of refocusing described above for the Lotto painting. 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. We note, however, that none of the conclusions from our calculations are sensitive to the precise height of the flame. 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.

If the overall image of this chandelier is based on an optical projection, it is reasonable to expect that, after correcting for perspective, the positions of the tops of each of the six candle holders should exhibit something very close to perfect hexagonal symmetry. If, on the other hand, van Eyck painted this very complex three-dimensional object only

Fig. 4. Chandelier in the *Arnolfini Marriage* (detail). It can be seen from this image that the decorative features above and below each of the six main arcs would have been attached individually (by soldering or riveting), making their locations completely unsuitable for any analysis of the perspective of this painting. This is confirmed by the findings of Fig. 6.

by observation, large deviations should occur in the positions of these candle holders. The blue dots in Figure 5 are the positions of the tops of each of the candle holders in the painting after correcting for perspective (i.e. to convert it to a plan view as viewed from the beneath the chandelier, with the candle holders nearest to the viewer at the top of this figure). As can be seen, the agreement with the points of a perfect hexagon is remarkable. The hexagon is rotated 6^o counterclockwise, which is due to the chandelier being viewed from that angle. The maximum deviation of any of the cadle 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. As Figure 7 shows, the arms of a 21st century light fixture show imperfections comparable to those on van Eyck's chandelier.

While it would have been relatively easy to have accidentally bent the angular positions of such chandelier arms with respect to each other, or to have attached them with slight errors to the central core, it would be much less likely that the lengths of the arms would vary significantly. Hence, if this painting is based on an optical projection, we would expect the radial positions of the candle holders to deviate much less than their angular positions. Shown in yellow on Figure 5 is a circle through the perspective-corrected positions of the candle holders. As can be seen, the radial positions are identical to within a worst case of only 7.4 mm; i.e., only 1.5% of the radius of the chandelier.

Figure 6 shows the shapes of the perspective-corrected arms of the chandelier, each outlined in a different color, and with the three arms to the viewer's right flopped horizontally so all six overlap. Where the painting doesn't show a complete arm because it is partially hidden by the arms in front of it, only the visible portions are outlined. As can be seen, the main arcs of all six arms are identical to within 5% in width and 1.5% in length. The latter figure is completely consistent with the above, independent, analysis of the radial positions of the candle holders. However, as would be expected for such a complex, hand-fabricated object, there are large variations in the positions of the decorative features attached to those arcs, confirming their uselessness for any sort of perspective analysis.

Given that the arcs themselves are nearly identical, the lowest point on the position of each arc provides an independent set of data to analyze in the same way as we did with the candle holders. With one exception, these lowest points, when corrected for perspective, are in excellent agreement with the same 6^o-rotated hexagon as the candle holders. That one exception is the arm extending directly to the viewer's right, which is significantly below the position it would have if it had been faithfully traced from an optical projection (it is nearly the full width of the arm lower than the predicted position).

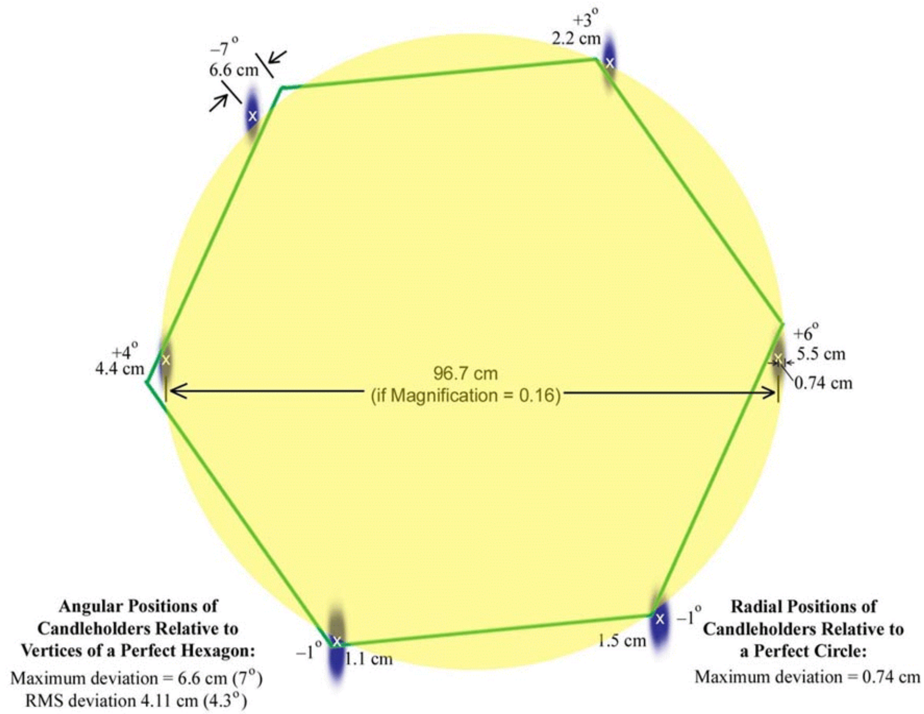

Fig. 5. The blue ovals mark the perspective corrected positions of the tops of the six candle holders in the *Arnolfini Marriage*. In green is a hexagon, rotated by 6°. The rms deviation of the angular positions of the candle holders from this hexagon is only 4.3°, with a maximum deviation of 7°. Assuming a magnification of 0.16 as determined from the measured height of a candle flame, the yellow circle through the candle holders has a diameter of 96.7 cm. The maximum radial deviation of any of the six candle holders from the radius of this circle is only 7.4 mm (1.5%).

To summarize the evidence that van Eyck's painting of this chandelier is based on an optical projection:

1) The perspective-corrected length, width, and shape of the main arc of all six arms are identical to within ~2%;

2) The perspective-corrected radii of all six candle holders are within ±1.5% of the radius of a perfect circle centered on the axis of the chandelier;

3) The perspective-corrected angular positions of all six candle holders are within ±4° of the points of a perfect hexagon;

4) To within ±1 mm on the painting, the positions of the lowest points on the arcs of five of the six arms have the identical perspective-corrected hexagonal symmetry as the candle holders, with both sets of data rotated by the same 6°;

5) The vanishing points defined by the candle holders as well as by the lowest positions of the arcs converge to the same horizon to within the accuracy expected for the imperfections in a real chandelier;

6) Qualitative: the overall size of ~1 m estimated from the height of the candle flame is physically reasonable, as are the minor variations in the lengths and angles for such an ornate, hand-made object. Our analysis of photographs of two six-arm lighting fixtures (one of which is shown in Fig. 3) taken from approximately the same viewpoint as the chandelier finds angular and radial deviations of the perspective-corrected positions of their light bulb holders of relative size comparable to that of van Eyck's chandelier, as well as perspective lines that do not come to well-defined vanishing foci on a single horizon line.

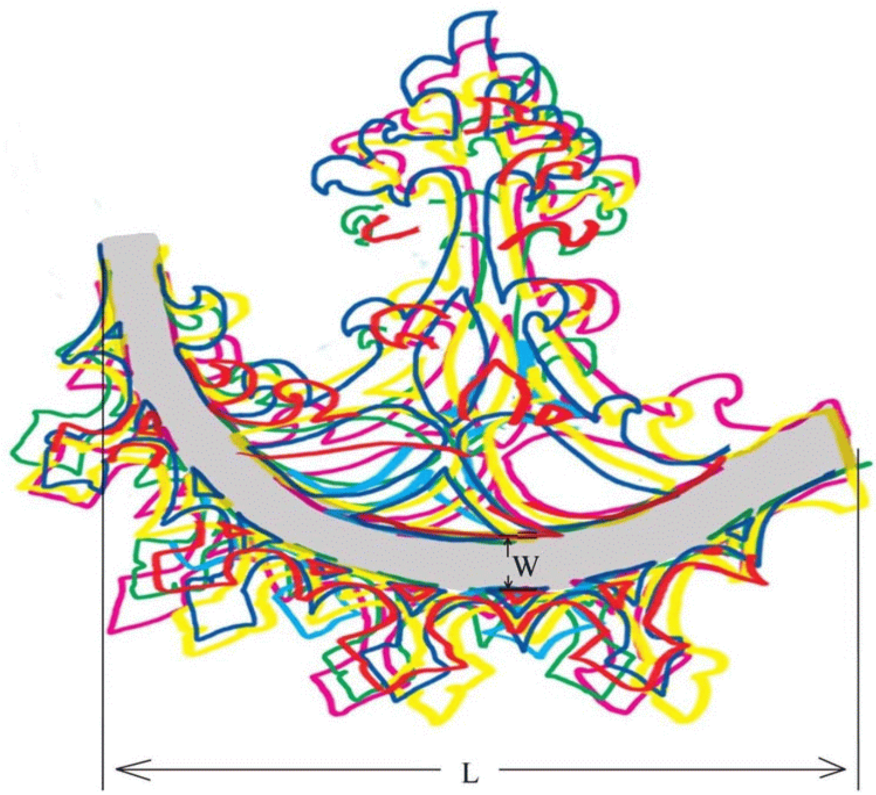

Fig. 6. The outlines of all six arms on the Arnolfini chandelier in different colors, corrected for perspective and with the arms to the viewer's right flopped horizontally to overlay on the arms to the left. As can be seen (highlighted in grey), the main arc of all six arms are the same to within 1.5% in length and 5% in width. However, as would be expected, there are significant variations in the locations where the decorative elements are attached to each of the arms.

From the above evidence, with a high degree of certainty we can conclude that van Eyck's chandelier is based on an optical projection of a real chandelier. Although there are some small differences (e.g. the height of one arm) that provide insights into artistic choices van Eyck made to deviate from tracing the projection, possibly to accentuate some features, overall the remarkably realistic perspective of this complex object is a result of the optical projection technique used as an aid by the artist.

4. Summary and Conclusions

The elements of three paintings we have analyzed 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 this evidence shows that *some* features of *some* paintings were produced with the aid of lenses. However, 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

5. Acknowledgments

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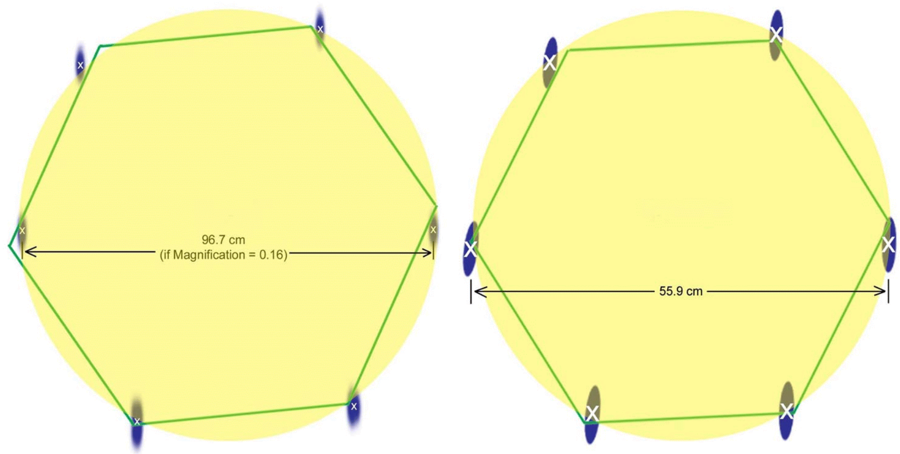

Fig. 7 (left) The *Arnolfini* chandelier analysis of Fig. 5. **(right)** The same analysis done to the light fixture at the bottom of Fig. 3. Note that the imperfections in this 21st century light fixture are comparable to those of the 15th century chandelier.

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