TECHNICAL ARTICLE

Image Contour Fidelity Analysis of Mechanically Aided Enlargements of Jan van Eyck's Albergati Portrait

Marco F. Duarte
and David G. Stork

ABSTRACT

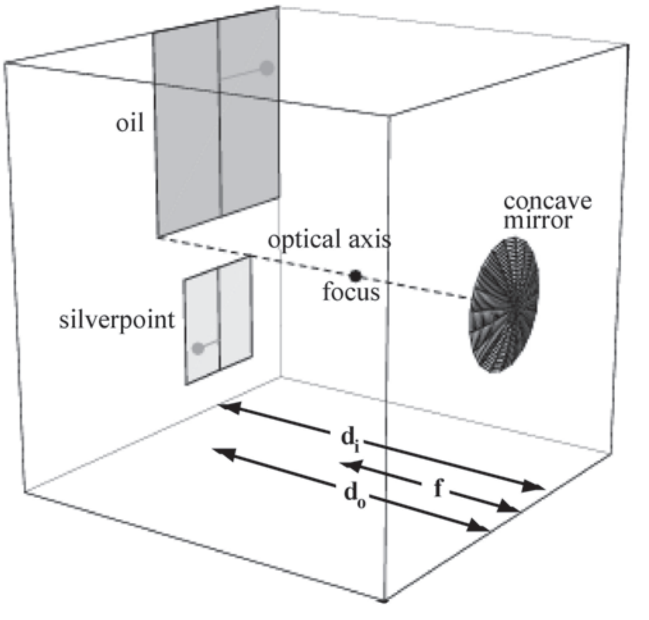
A recent revisionist theory claims that as early as 1430 European artists secretly invented optical projectors and used them as aids during the execution of their paintings. Key artworks adduced in support of this theory are a pair of portraits of Cardinal Niccolò Albergati by Jan van Eyck: a silverpoint study (1431) and a formal oil work (1432). We tested whether the use of known contemporaneous mechanical methods might explain this image evidence as well as the use of optical methods, also explaining additional physical evidence. We used traditional image processing techniques, as well as "re-enacted copies" by professional artists using mechanical methods. We found that the fidelities of these modern "re-enactments" were equal or superior to those of the van Eyck works.

In considering the grand sweep of the development of Western painting, contemporary artist David Hockney highlighted the arrival of new art at the dawn of the Renaissance. He interpreted the rise in realism emerging in the work of Flemish masters Jan van Eyck, Robert Campin, Dieric Bouts, Rogier van der Weyden and several others as indicating a new, "optical" way of representing the world [1]. He suggested that this new way of seeing was sparked by the discovery of images projected optically by, for instance, concave mirrors. This claim about artistic *influence* is difficult, if not impossible, to test scientifically, given the absence of supporting documentary evidence [2] and given alternate plausible explanations consistent with the evidence from the paintings themselves [3]. For this reason we shall not address this speculation.

Hockney's additional claim is perhaps bolder: that these early Renaissance painters *directly used* projected images during the execution of their works—a claim about artistic practice or *praxis*. We address this latter claim here. If it could be proven that any of these early Renaissance masters employed projections roughly 200 years earlier than scholars have firm evidence of anyone tracing a projected image (Johannes Kepler, 1603), such a discovery would have great import for our understanding of the development of image-making and art. The procedure would be the earliest direct precursor to the *chemical* recording of projected images in photography.

Our research presented here addresses the tracing claim for van Eyck's *Portrait of Cardinal Niccolò Albergati* (1431 and 1432)—actually two portraits: a small informal silverpoint study and a subsequent larger oil portrait copy. We consider whether the high fidelity of the oil work implies that van Eyck traced an optical projection when copying the silverpoint study or whether he might have instead used mechanical drawing aids. We perform a thorough study of contour similarity across different copies of the original portrait. In the next section, we briefly review Hockney's projection theory and his specific claim about the Albergati oil portrait. The third section, Copying/Enlarging Experiments, describes the copying and enlarging techniques known from early Renaissance Europe and the copies of van Eyck's silverpoint created by professional realist artists using these methods. The fidelity of these copies will be judged based on their major contours and outlines, not the fine details such as hair or shaded passages such as the cheeks, and therefore we digitally processed these works to isolate their major contours. We describe such processing—edge detection, thresholding and line-thinning—in the section Image Pre-Processing. The theoretically justified metric for fidelity we use is based on the Chamfer distance or Chamfer measure, which we review in the fifth section, Chamfer Distance and Fidelity Measurements. We present our experimental fidelity results in the sixth section and our experimental "relative offset" results in the seventh section. We close with a conclusion and summary remarks.

Fig. 1. This schematic of Hockney's epidiascope shows the silverpoint, the support for the oil copy and the concave projection mirror. (© David G. Stork)



Marco F. Duarte (student), Department of Electrical and Computer Engineering, Rice University, 6100 Main Street, MS-366, Houston, TX 77005, U.S.A. E-mail: <duarte@rice.edu>.

David G. Stork (scientist and professor), Ricoh Innovations, 2882 Sand Hill Road, Menlo Park, CA 94025 U.S.A., and Department of Statistics, Stanford University, Stanford, CA 94305, U.S.A. E-mail: <artanalyst@gmail.com>.

Fig. 2. Each of the three "matched correspondence passages" identified by Hockney and Falco, shown here on the silverpoint, correspond well to those on the oil copy for a single relative offset. That is, at one relative offset between the silverpoint and oil copy, the eyes, nose, mouth, chin and cheek overlap accurately (outlined at left), but the other passages of the images do not. For a different relative offset, the earlobe and collar and portion of the shoulder overlap accurately (outlined at bottom right), but the other passages of the images do not. Likewise at yet another relative offset, the pinna and much of the ear overlap accurately (outlined at top right). (© Marco F. Duarte)

Fig. 3. The van Eyck silverpoint and oil copy processed to isolate the major contours, and the oil image (dark) scaled to match that of the silverpoint (light) based on the eyes, nose, mouth, chin and left cheek (left area in Fig. 2). The images were then aligned for maximum overlap of the upper ear region (top right area in Fig. 2). (© Marco F. Duarte)

Hockney's Tracing Theory

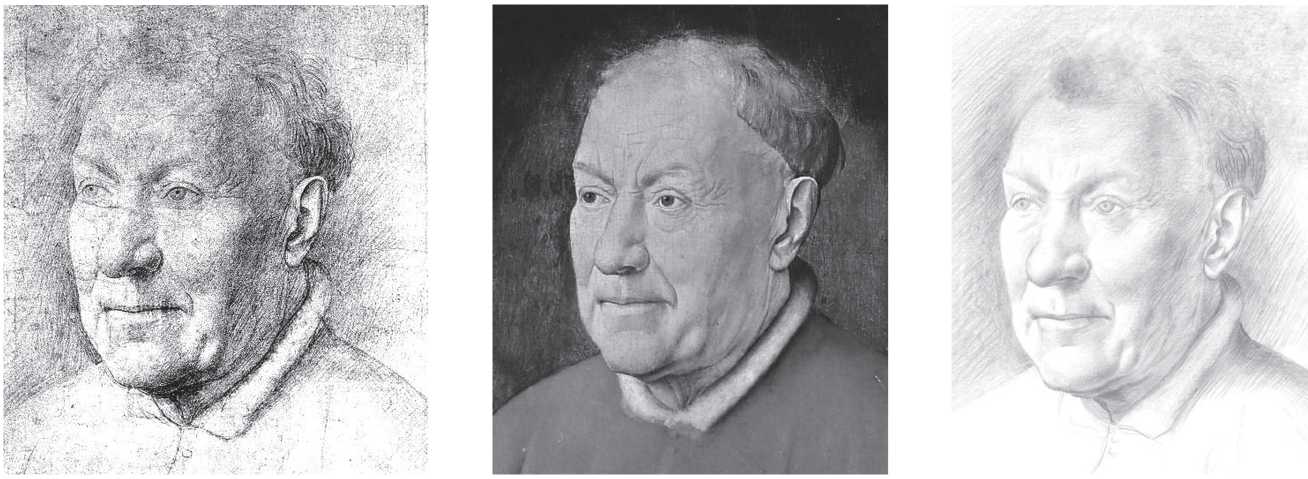
Considering the grand sweep of the development of Western painting, the contemporary painter, photographer and set designer David Hockney paid particular attention to the dramatic rise in realism apparent in the works of Flemish artists of the early Renaissance, such as those by Jan van Eyck, Dieric Bouts, the Master of the Flémalle and Rogier van der Weyden. He made a claim associated with this new "optical look," as he called it [4], that is open to technical evaluation: that some artists secretly used projected images *directly*—specifically that they traced images during the execution of passages within their paintings. Traced images would likely bear perspective and form information that could be revealed through technical image analysis and computer vision. It is this claim regarding artistic praxis that we address.

Hockney's Optical Projector

Hockney claimed that some early Renaissance painters traced optically projected images during the execution of their works. He and his collaborator, thin-film physicist Charles Falco, strongly preferred the theory of the use of concave mirrors as the purported optical instruments over converging lenses for two reasons [5]. First, concave mirrors preserve the left-right symmetry of the image—that is, a tracing of the projected real, inverted image on a canvas or other support, when rotated right side up, possesses the same lateral symmetry of the scene: The image of a *right-handed* subject appears *right-handed* in the final artwork. In contradistinction, the image projected by a converging lens (which lacks mirror reflection) reverses the symmetry of the scene: The image of a *right-handed* subject emerges *left-handed*, posing an impediment to the artist. Hockney and Falco's second reason for favoring concave mirrors over converging lenses was that they felt art historians, and perhaps even historians of optics, might be unfamiliar with the imaging properties of such mirrors and hence might have overlooked contemporaneous textual evidence showing artists used projection mirrors. In short, in favoring the concave mirror theory Hockney and Falco tried to explain, in part, the lack of textual evidence for optical projections onto a screen (see Conclusions and Future Directions).

Hockney and Falco's specific claim for the Albergati portraits is that van Eyck copied and enlarged his silverpoint study by means of an *epidiascope*, or simple opaque projector, as sketched in Fig. 1. The silverpoint study would have been held in very bright light such as sunlight [6], perhaps on an easel, the support for the oil work being held in the dark, on a second easel. The concave mirror would project an inverted image of the silverpoint drawing onto the wood panel support, which the artist would trace and, later, paint over in oil. The magnification, M, produced by such a device is equal to the ratio of the distances from the image to the mirror, d_i, to that of the object to mirror, d_o, that is, $M = d_i/d_o$. (For van Eyck's Albergati portraits, M is roughly 1.4.)

If van Eyck accurately traced such a projected image, the fidelity of the copy—revealed through digital scanning and suitable scaling (a reduction)—should be high. That is, the contours of the oil portrait and of the silverpoint should align very closely. Perhaps, however, this fidelity would also be high if he had used a mechanical device such as a reducing compass, or a grid construction [7], or even unaided—"eyeballing," as Hockney calls it. If realist artists using such non-optical aids can indeed attain fidelity comparable to that found in van Eyck's works, then Hockney's tracing would fail



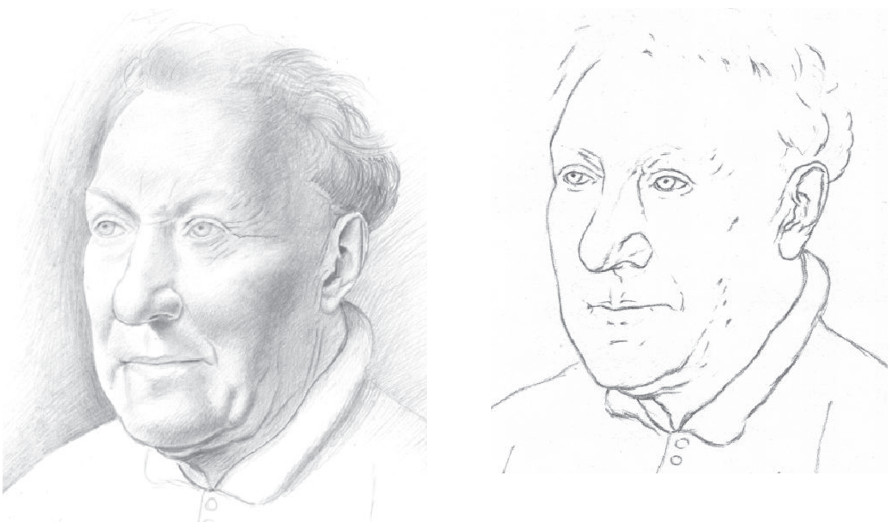


Fig. 4. Renditions of Cardinal Niccolò Albergati (from top left): (a) Jan van Eyck, *Cardinal Niccolò Albergati*, silverpoint on white paper, 21.2 × 18 cm, 1431, Staatliche Kunstsammlungen, Dresden. (b) Jan van Eyck, *Portrait of Cardinal Niccolò Albergati*, oil on wood panel, 34.1 × 27.3 cm, 1432, Kunsthistorisches Museum, Vienna. (c) Pico van de Werken, freehand copy of the van Eyck silverpoint, pencil on paper, 46 × 30 cm, 2006. (© Pico van de Werken) (d) Ramon van de Werken, Reductionszirkel-assisted copy of the van Eyck silverpoint, pencil on paper, 46 × 30 cm, 2006. (© Ramon van de Werken) (e) Tim Stotz, grid-assisted copy of the van Eyck silverpoint, pencil on paper, 46 × 30 cm, 2005. (© Tim Stotz)

to attain persuasive support [8]. Conversely, if artists using non-optical methods cannot attain the high fidelity found in van Eyck's works, then the optical tracing theory would gain some support. Of course this latter, negative, result would not *prove* the tracing claim, as it might be that the particular artists demonstrating the non-optical technique were not as careful or accurate or motivated as van Eyck drawing "by eye" or using non-optical aids.

In addition to the high fidelity of van Eyck's copy, there is, further, distinctive visual evidence that may provide information about his copying method: "relative shifts" or "relative offsets" [9]. If the oil work is digitally reduced to match the scale of the silverpoint and the two images are overlapped for maximum contour correspondence, the eyes, nose, mouth, chin and cheek at the left indeed overlap quite closely, that is, reveal the high fidelity described above. However, for these works, it then so happens that the ear and shoulder passages at the right do not overlap but instead are offset or shifted with respect to one another. If the silverpoint image is shifted to the right and slightly downward, then the earlobe and shoulder regions overlap closely (but then of course the nose, chin, eyes and left cheek do not overlap closely). Likewise, if the image of the silverpoint is shifted up and slightly to the right, then the pinna, or top of the ears, overlap well.

For the above reason we say that there are "matched correspondence passages," that is, regions (passages) that coalign well at one relative offset but not at another. Hockney and Falco claim that these matched correspondence passages arose when van Eyck made a mistake and accidentally "bumped" his projector in mid-execution of the copy and then completed the copy with the now shifted image [10]. In the epidiascope explanation, one could thus consider these regions as arising from three "exposures." Figure 2 shows these three matched correspondence passages.

There is an immediate and direct challenge to the tracing claim presented by this evidence of relative offsets. If van Eyck had accidentally bumped his epidiascope midway through executing the copy, he would surely have seen the conspicuous mismatch between his tracing already committed to the oak panel support and the now shifted projected image, such as is evident in Fig. 3. Moreover, this mismatch would have been quite salient had van Eyck been observing the images while one of them was *moving* with respect to the other, because relative motion is an extremely powerful perceptual and segmentation cue [11]. It seems far more likely that he deliberately altered the position of the ear and other regions for artistic reasons while executing his copy, no matter which copying technique he used.

There is, further, distinctive physical evidence borne by the silverpoint: distinctive pinprick holes along the contours, discovered by an interdisciplinary team of art conservators and physicists [12].

These distinctive pinprick holes play no role whatsoever in any epidiascope explanation. After the discovery of these distinctive pinprick holes, Falco noted that nine pinpricks in five locations was too small a number for van Eyck to achieve this fidelity [13]. Our experimental evidence below, though, shows that high resolution can be achieved by eye, without any pinprick holes. Furthermore, the use of such a mechanical device need not necessarily lead to pinprick holes because the artist could *gently* place the tips of the device on the original or the copy, thus leaving no incisions or holes. As such, the nine pinprick holes represent a *lower limit* to the number of times he placed the device on the silverpoint.

In a recent study, Marciari and Verstegen studied the extensive use of scaled preparatory drawings by Barocci (c. 1535–1612) [14]. When such drawings are compared to a half-sized or one-third-sized version of the painting, they "match it perfectly." They interpret this image evidence as showing Barocci used a reducing compass. Note, too, that they report no pinprick holes; moreover, Barocci's brother is known to have fashioned such compasses [15]. This evidence shows that a dividing compass can be used without leaving any pinprick holes. Hence, the discovery of nine such holes in the *Albergati* drawing indicates a lower limit on the number of measurements that van Eyck could have made.

If van Eyck had indeed used a reducing compass, it is conceivable that such a device would have left pinprick holes in the *copy* support as well. In July 2005, one of the current authors (Stork) and the curator of paintings examined very closely the Albergati oil work in the galleries of the Kunsthistorishes Museum Vienna, using grazing flashlight illumination and a magnifying glass, as well as its X-ray in the museum archives. No matching pinprick holes were visible in the copy. As with the silverpoint, however, an artist can use a mechanical aid yet leave no conspicuous marks in the copy work.

If van Eyck had enlarged the silverpoint by eye (without drawing aids) or by mechanical methods described in the next section, there would be no such conspicuous mismatch. For instance if the artist had copied the left side of the face and then deliberately chosen to place the ear somewhat to the right (for artistic reasons), he would have seen no mismatch or offset of the ear, because there would be no projected image as referent.

Copying/Enlarging Experiments

In order to test whether van Eyck might have copied his silverpoint study using non-optical methods, we asked realist artists to "re-enact" or "demonstrate" copying by such non-optical methods and then measured the fidelities of their final works. All experimental copy enlargements were executed by accomplished, established professional artists as (unpaid) assistance in support of our research. These artists were instructed to make as faithful, geometrically accurate a copy of a print of the silverpoint as possible, roughly 40% larger than the original. They used techniques that were known in the early 15th century and consistent with the physical evidence (specifically, the pinprick holes) in the van Eyck works. The artists were told that their works were to be judged on the fidelity of the principal contours, not on shading and not on accuracy of overall scale (see Relative Offset Results below). The three methods we tested were:

1. Unaided or "eyeballing": Dutch artist Pico van de Werken copied the silverpoint entirely by eye, without

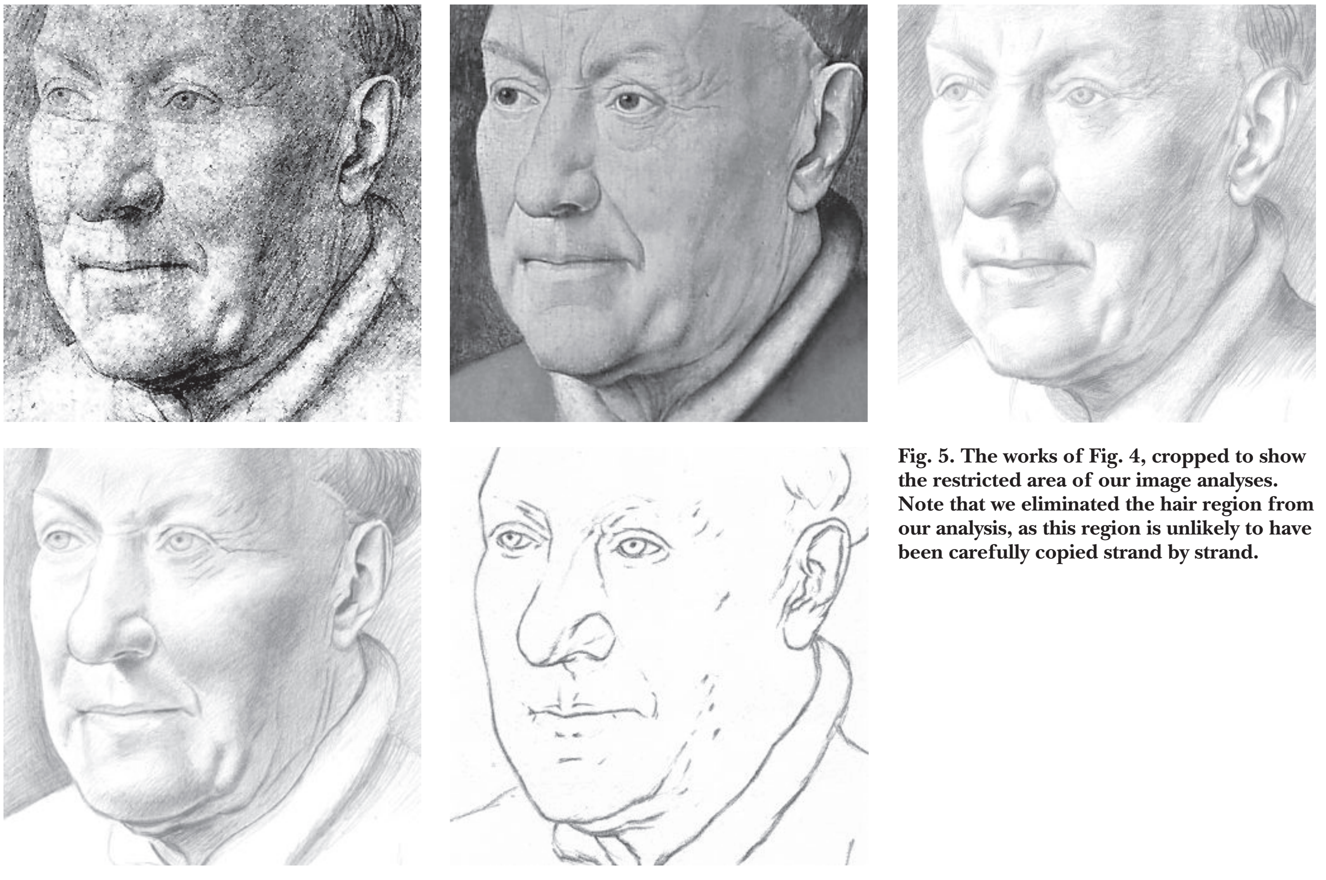


Fig. 5. The works of Fig. 4, cropped to show the restricted area of our image analyses. Note that we eliminated the hair region from our analysis, as this region is unlikely to have been carefully copied strand by strand.

any mechanical or optical aids of any sort. The artist can use many different techniques for judging *distances* that are prevalent among otherwise unaided realist artists when drawing from real life or when copying two-dimensional works.

2. *Reductionszirkel* or reducing compass: Dutch artist Ramon van de Werken copied the silverpoint by means of a modern, commercial reducing compass. Such a device looks much like the familiar hinged compass used in constructions in mathematical geometry, but with an added leg whose position is yoked to that of the other two legs [16].
3. Grid construction: The simplest grid-based method for copying and enlarging a 2D original is to draw a square grid over the original and a larger grid on the copy support and then to mark corresponding points on the copy. American artist Timothy Stotz copied and enlarged the van Eyck silverpoint by means of a faint grid on a paper support. He later erased the faint grid lines. His method is comparable to using a thread grid over the works, which would have left no trace on the works and would thus be consistent with the image evidence in van Eyck's works.

Figure 4 shows van Eyck's works and the copies produced by the methods just described. The artist using a grid construction executed merely the outlines, which were all that were required for our analysis. The artist using a reducing compass and the artist using no aids shaded and highlighted their works, as is their typical portrait method.

Image Pre-Processing

It is unlikely that van Eyck copied each individual hair or the shading and contours of Albergati's jacket; thus we based our fidelity estimates on the face and its adjacent regions. For this reason we first scaled and cropped all images to isolate the same region of Albergati's face, as shown in Fig. 5. We were careful to scale each image uniformly, that is, ensure the same magnification in the horizontal and the vertical directions. Distances between the face's features, such as between eyes and from eyes to mouth, were used to scale the drawings uniformly.

We then isolated the major image contours semi-automatically. First, we applied a standard Canny edge detector [17], implemented in Matlab, to each image. The resulting key contours are shown in Fig. 6. Note especially that even the best resulting edge map for the silverpoint is quite noisy, containing a number of short, isolated, spurious contours.

Figure 7 shows the final edge maps, that is, after hand editing. Note that the edge map of the original silverpoint remained somewhat noisier than the edge maps of the other images. We did not hand edit the silverpoint extensively, as the noise seemed random and would not introduce any systematic error; it would not be biased to be more similar to any one copy's edge map than another. In short, further hand editing of the contours would not likely change the relative rankings of the fidelities so as to affect our key conclusions.

Chamfer Distance and Fidelity Measurements

A principled measure for comparing shapes, widely used in computer vision and pattern recognition, is based on the *Chamfer distance* or *Chamfer transform* [18]. The Chamfer distance between two single-pixel thin digital curves, Γ_1

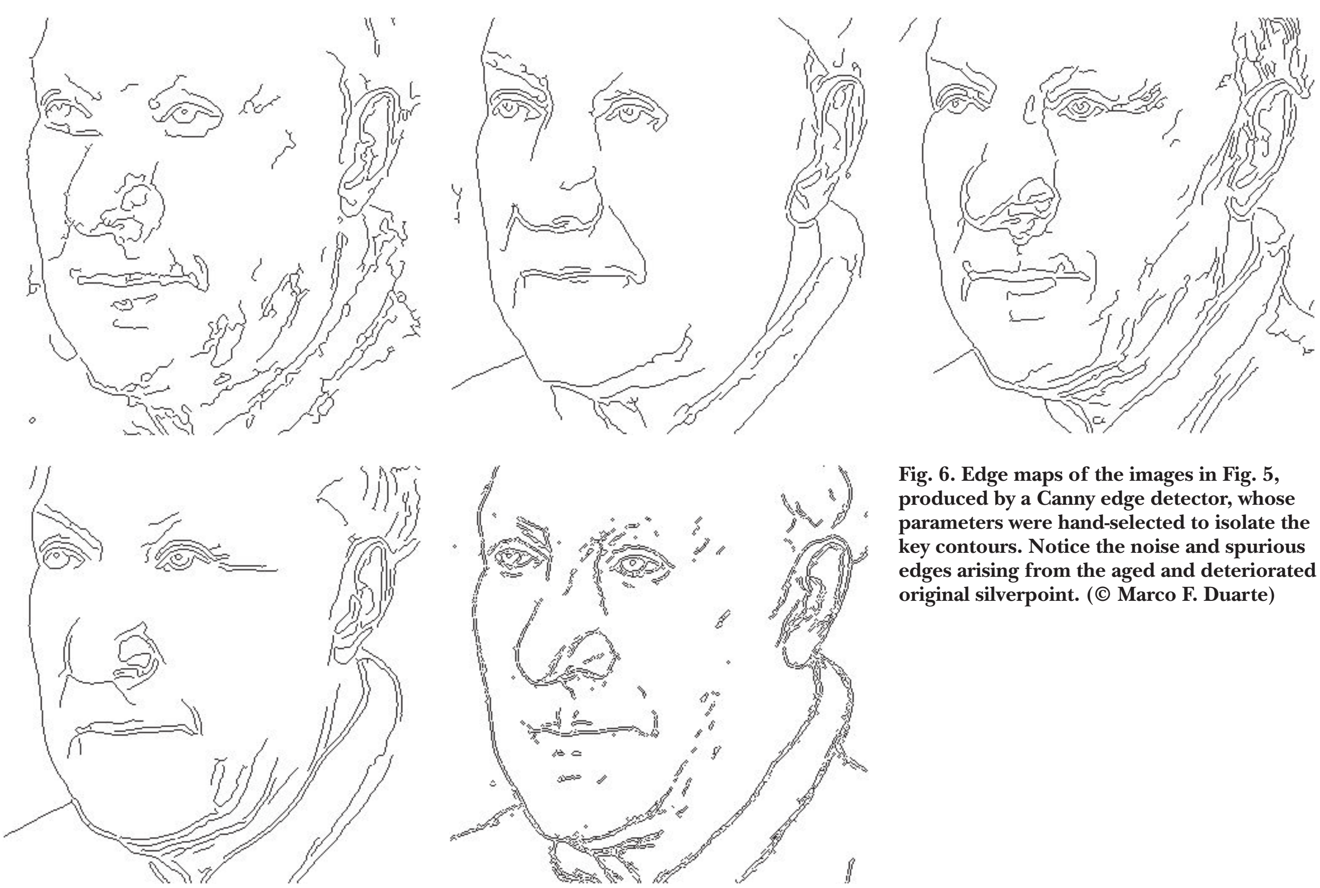
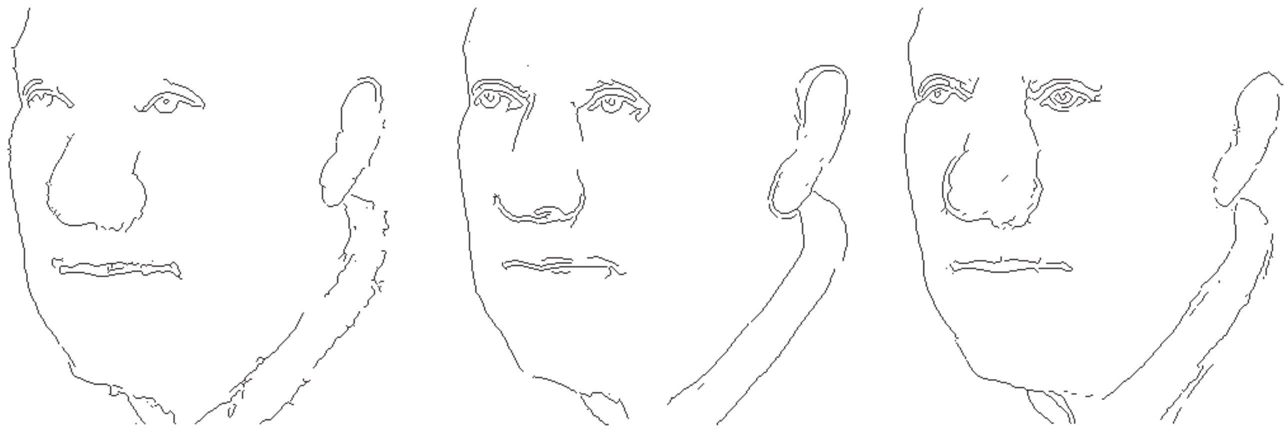


Fig. 6. Edge maps of the images in Fig. 5, produced by a Canny edge detector, whose parameters were hand-selected to isolate the key contours. Notice the noise and spurious edges arising from the aged and deteriorated original silverpoint. (© Marco F. Duarte)



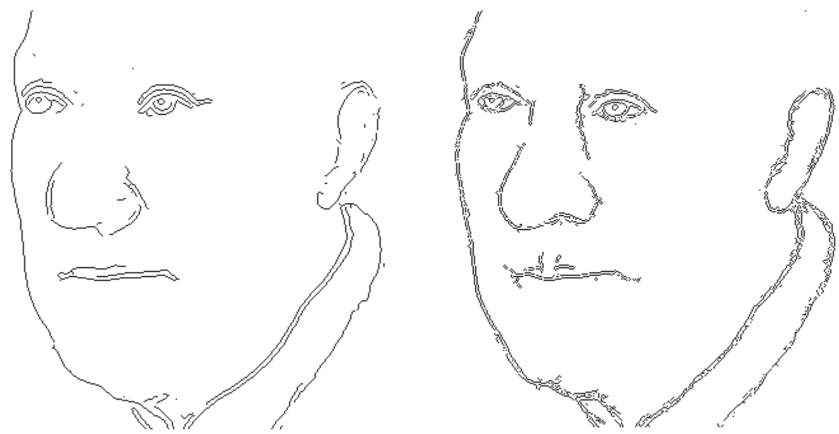


Fig. 7. Hand-edited versions of the intermediate edge maps of Fig. 6. Spurious contour segments were eliminated from various images but in no case were any contours added or their locations changed. (© Marco F. Duarte)

and Γ_2, is computed as follows. For each point on Γ_1 we find the distance to the nearest point on Γ_2, then sum these (non-negative) distances over all points in Γ_1. Finally, we divide this sum of distances by the number of points on Γ_1. In this way, then, the Chamfer distance between Γ_1 and Γ_2 is the (unweighted) average distance of an arbitrary point on Γ_1 to the nearest point on Γ_2. Clearly the Chamfer distance between a curve and itself is 0 but the Chamfer distance can vanish in other cases too, for instance if the points of Γ_1 form a proper subset of Γ_2. The Chamfer distance is a principled measure of the similarity of two curves or contours; the larger the Chamfer distance the more dissimilar the curves.

One way to represent the Chamfer distance is the *distance transform* of a curve or set of points: a figure that illustrates the distance between the curve and each point in a region. Color Plate D shows the distance transform of the hand-edited silverpoint edge map. The color of each pixel represents the distance to the nearest point on the edge map: blue is close, red is far. The Chamfer distance between a candidate curve, Γ_2, and the silverpoint, Γ_1, can be computed by simply summing the distance values corresponding to the pixel positions of Γ_2 in the distance transform of Γ_1, then dividing by the total number of points in Γ_2.

Given the evidence of relative shifts in the van Eyck oil, it would be inappropriate to calculate the fidelity based on this image overall: there would be large errors (high Chamfer distance) for the shifted portions of the image. For this reason we calculated the Chamfer distances in three portions, corresponding to the "exposure" passages shown in

Fig. 8. Overlap of edge maps of the van Eyck silverpoint (dark) and (a) van Eyck oil (light) and (b) unaided (PvdW) (light). (© Marco F. Duarte)

Fig. 2. We likewise calculated the Chamfer distances of the other copies in these three passages.

Fidelity Results

Table 1 shows the relative Chamfer distances for the three passages defined above. The table also shows the relative Chamfer distance for the full face, computed for van Eyck's oil work as the average of the three component Chamfer distances, weighted by contour length.

Notice that in two of three regions, and overall, the van Eyck oil work had the largest Chamfer distance, that is, the lowest fidelity. For the other regions, the mechanical reproduction methods obtained the highest fidelities.

Because our results involved different artists with possibly different realist talent and effort, our results, taken alone, are insufficient to make strong claims about the overall relative merits of one enlarging method over another except to say that it is very clear that talented realist artists can achieve fidelity comparable to that in van Eyck's oil work using non-optical methods. Perhaps the most surprising result of our research was the high fidelity an artist can achieve without any aids whatsoever.

Another informal way to represent the high fidelity of non-optical copying/enlarging is by inspection, such as presented by Hockney and Falco [19]. Figure 8 shows overlap of edge images for the van Eyck oil painting and for the freehand ("eyeballed") copy, with scaling and offset for maximum correspondence along the cheek line. (Note the offset of the ear in van Eyck's oil portrait at the left, as discussed above.) Clearly the freehand drawing is at least comparable to the fidelity of the oil copy.

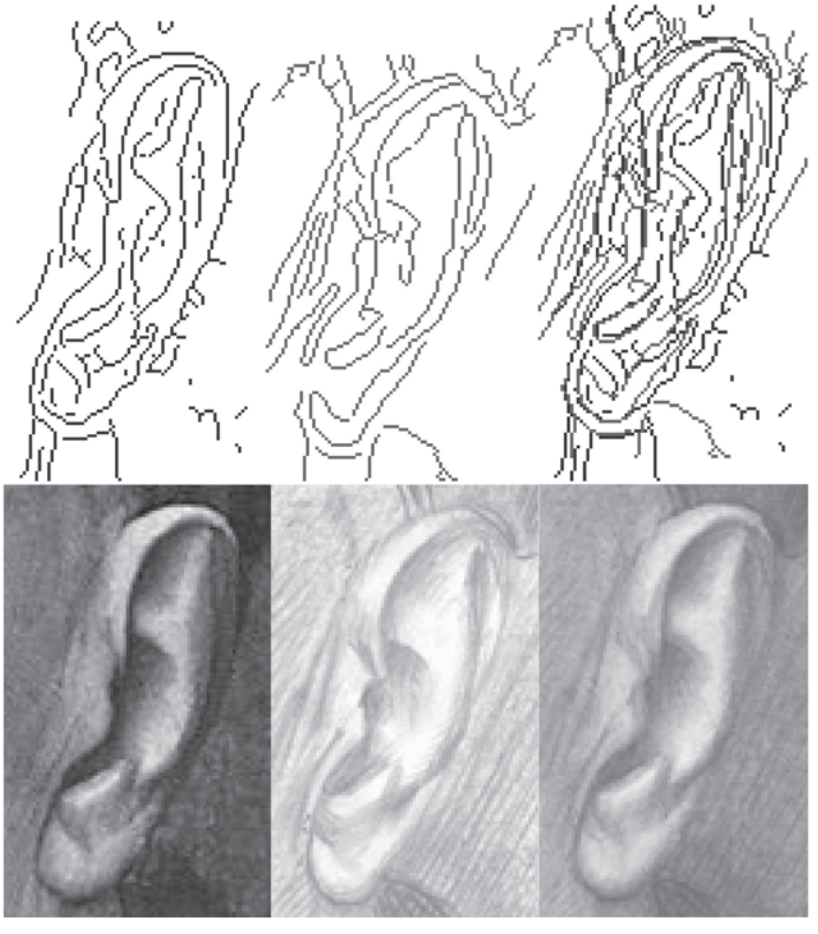
Relative Offset Results

As mentioned above, the second class of evidence adduced in support of the tracing theory concerns "relative offsets."

Falco has pointed out that if an artist used optics he need not "slavishly" trace a projected image, that is, the artist would be free to adjust the positions and sizes of passages for artistic or other reasons. Of course, by the same token, an artist *not* using optics is similarly free to adjust the position or size of a passage for artistic or other reasons. Hockney and Falco have interpreted the deviation from overall fidelity as due to "bumping" a projector in mid-execution, but this visual evidence is just as consistent with the artist altering the positions for artistic reasons.

Consider Albergati's ear, which Hockney and Falco claim was executed in two "exposures" shifted with respect to each other. However, an artist working by eye could easily have drawn this ear at its position and scale. Figure 9 shows the ear from the van Eyck oil copy, and from the modern drawing done by eye (PvdW), matched in scale. The right side of the figure shows these two edge maps and two images overlapped. There is clearly excellent agreement. In short, this evidence shows that van Eyck could easily have drawn the ear without discrete "relative shifts" from a "bumped" optical system. As such, the visual evidence of deviation from overall fidelity need not arise from a "bump." In short, this evidence does not confirm the use of optical projections.

Fig. 9. Edge maps (top) and corresponding image passages (bottom) for different versions of van Eyck's ear. *Left*: ear from van Eyck oil painting. *Middle*: modern "re-enactment" drawn by eye (without optical or other aids), scaled uniformly to match that of the ear painted by van Eyck. *Right*: previous two ears overlapped. (© Marco F. Duarte)



In short, we need not accept that there were three "exposures," or two "relative shifts." Yes, one can get an acceptable fit to the data by assuming such shifts, but other procedures fit the image data equally well. For instance, the artist working by eye could easily have scaled (and displaced) the ear. There would have been no "error"; in fact, we showed that the fit of such a scaled-shifted ear is perfectly acceptable. In computing the total Chamfer distance in three portions, we are giving the benefit of the doubt to Hockney's claims.

The relative shift (including, more properly speaking, the rescaling of the ear) is easy to explain for eyeballing and reducing compass: the artist simply scaled and shifted the position of the ear. Likewise, in the "eyeballed" image the shoulder appears shifted, but there is no reason to state that this was a discrete shift of the form proposed by Hockney.

Without documentary evidence, one can rarely *prove* the artist's method of executing half-millennium-old artworks. Our goal here has been to show that non-optical methods are not merely *possible* but indeed more *plausible* than the optical methods.

Conclusions and Future Directions

Our central conclusion remains: van Eyck, often considered the greatest draftsman of 15th-century Europe, could indeed have achieved the fidelity and "relative shift" evidence found in his Albergati portraits without recourse to tracing an optical projection. Our conclusions are enhanced by the larger consideration of details of the portrait, such as segmentation and relative offsets. Although one cannot *prove* that an artist used a particular method a half millennium ago, we find implausible that van Eyck traced an optically projected image when copying the silverpoint in light of:

- the lack of any contemporary documentary record describing the tracing procedure in general
- the lack of contemporary documentary record describing its use in art, or for any works by van Eyck or his artistic contemporaries
- the lack of evidence for required high-quality concave mirrors [20]
- the distinctive physical evidence of distinctive pinprick holes consistent with mechanical (not optical) methods
- our experimental fidelity and scaling results presented above.

Of course, the burden of proof lies foursquare upon the revisionists who freely admit they are proposing a fundamentally new procedure in early Renaissance art praxis, that is, upon Hockney and Falco. It is not sufficient for them to find image evidence that might be merely *consistent* with the use of projection optics, rather they must show that non-optical methods (mechanical, eyeballing, etc.) could *not* have been used. In light of all the evidence pertaining to the Albergati portraits, it is hard to see how the tracing theory's proponents might rise to that requirement.

Our methods may be of use in other art historical and curatorial research. For instance, Chamfer-based fidelity measurements might reveal forgeries among prints such as etchings, lithographs or woodblock prints. These techniques might provide a quantitative basis for judging the degradation of successive prints from a given etching plate, lithographic stone or woodblock. Perhaps a modified Chamfer distance (one where inter-point distances are weighted by factors informed by art-historical knowledge) might be useful for quantifying the changes in style throughout an artist's career. These methods build upon a growing set of techniques that have proven of use in the study of art—methods that, when understood and used in conjunction with traditional art-historical methods, promise to shed new light on art.

Acknowledgments

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Glossary

artistic influence—the indirect effect of one artist upon another, for instance the influence of Japanese art upon van Gogh.

Chamfer distance—a measure of the similarity in shape of two curves based on the average distance from each point on one curve to the nearest point on the other curve.

concave mirror—a bowl-shaped mirror that can project an optical image.

converging lens—a glass lens thicker in its center that can project an optical image.

epidiascope—an "opaque projector," in which a concave mirror or converging lens projects the image of one flat object (e.g. a document or artwork) onto a plane.

pouncing—a method for copying an artwork in which tiny holes are pricked through the support (e.g. paper) of the original and charcoal dust is forced through these holes onto the support of the copy image.

reducing compass—closely related to the Reductionszirkel or *compasso da reduzione:* a simple hinged mechanical device in which the artist adjusts the separation of two legs to match points on the original and two other hinged legs then indicate the corresponding scaled distance in the copy.

relative shifts or spatial offset—in the Albergati portrait, the apparent spatial shift of one portion in the copy with respect to other portions in the copy.

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Table 1. Chamfer distances between different copies and the edge map of the van Eyck silverpoint, measured in pixels. "Full Face" for the oil portrait represents the mean of the individual distances in the other three passages, each of which was computed after the optimal relative shift.

Region	Left (Face)	Bottom (Collar)	Top (Ear)	Full Face
oil portrait (JvE)	3.3427	2.5929	4.9541	4.1928
unaided (PvdW)	2.8082	3.7868	2.3745	3.5099
Reducing compass (RvdW)	2.7162	3.5052	2.8100	3.1733
grid (TS)	3.1709	2.6024	2.0578	3.1311N

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