

Aberration analysis of the putative projector for Lorenzo Lotto’s *Husband and wife*: Image analysis through computer ray-tracing

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ABSTRACT

A recent theory claims that the late-Italian Renaissance painter Lorenzo Lotto secretly built a concave-mirror projector to project an image of a carpet onto his canvas and trace it during the execution of *Husband and wife* (c. 1543). Key evidence adduced to support this claim includes “perspective anomalies” and changes in “magnification” that the theory’s proponents ascribe to Lotto refocusing his projector to overcome its limitations in depth of field. We find, though, that there are important geometrical constraints upon such a putative optical projector not incorporated into the proponents’ analyses, and that when properly included, the argument for the use of optics loses its force. We used Zemax optical design software to create a simple model of Lotto’s studio and putative projector, and incorporated the optical properties proponents inferred from geometrical properties of the depicted carpet. Our central contribution derives from including the 116-cm-wide canvas screen; we found that this screen forces the incident light to strike the concave mirror at large angles ($\geq 15^\circ$) and that this, in turn, means that the projected image would reveal severe off-axis aberrations, particularly astigmatism. Such aberrations are roughly as severe as the defocus blur claimed to have led Lotto to refocus the projector. In short, we find that the projected images would not have gone in and out of focus in the way claimed by proponents, a result that undercuts their claim that Lotto used a projector for this painting. We speculate on the value of further uses of sophisticated ray-tracing analyses in the study of fine arts.

Keywords: Hockney tracing theory, Lorenzo Lotto, *Husband and wife*, optical aberrations, concave mirror projector, Renaissance art, computer ray tracing, astigmatism, coma

1. INTRODUCTION

The use of projected images as painters’ aids is securely established in the 18th century, in the cityscape studies by the Venetian master Canaletto (1671–1751), in the 19th century, in some photography assisted paintings by the American realist Thomas Eakins (1844–1916), and in the 20th century, in works by numerous photorealists such as Richard Estes (b. 1932), Robert Bechtle (b. 1932), and others. A recent theory seeks to establish the tracing procedure as early as 1420, nearly a quarter millennium earlier than previously thought.¹ The theory’s proponents adduce Lorenzo Lotto’s *Husband and wife* (Fig. 1) as the key work, which serves as their “Rosetta stone,” which they claim “proves” that early Renaissance artists secretly traced optically projected images far earlier than previously thought. The evidence provided by the theory’s proponents centers on perspective anomalies, changes in “magnification,” and a “blurred” area in the central keyhole in the depicted carpet. They claim Lotto refocused an optical projector to overcome its limited depth of field and that this was the source of this image evidence.² They solve coupled nonlinear equations and adjust a number of parameters (three-dimensional locations of the mirror, its focal length, aperture, two-dimensional orientations, position of first focus, etc.) to fit this image data to three significant figures, a procedure that shows they believe Lotto very accurately, “photographically”—even “slavishly”—traced parts of the purported image.^{3,4}

The central contribution of our paper is to show that when all necessary elements of the studio are included in the analyses, the proponents’ argument fails: in fact, there would have been no sharp projected image but most importantly no *change* in sharpness of the form essential to their refocusing explanation.

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Figure 1. Lorenzo Lotto, *Husband and wife* (c. 1543), 96 × 116 cm, oil on canvas, The State Hermitage Museum, St. Petersburg. The woman is holding a dog (*fido*), a traditional symbol of fidelity. The squirrel is a symbol of lustful wandering and the fact that the squirrel is *sleeping* (or dead), and that the husband is holding a paper bearing “HOMO NUN QUAM” (Latin, “man, never”), both indicate that the husband will not roam among other women. The couple is safe from the windy storm outside, showing their mutual support and refuge from the vicissitudes of life. Records show this painting was executed several years *after* the patron’s wife had died, and this may explain why her face is somewhat more ethereal than his (as if painted from descriptions) and, unusually for the period, higher than his (as if to indicate her otherworldly or even heavenly presence). The man’s eyes are slightly red, as if he had been crying. Thus this painting is likely the poignant record of the husband’s promise to remain faithful to his lost wife’s memory.

In Sect. 2 we review the tracing theory as applied to Lotto’s *Husband and wife* and in Sect. 3 describe earlier analyses of this claim. We revisit the reasons proponents prefer a concave mirror or “mirror lens,” rather than a converging glass lens, as the optical element and their explicit claim for the use of a concave mirror in the case of this painting. In Sect. 4 we present our new results. First, we identify a key element in the studio that was not incorporated into proponents’ model: the large canvas or screen. Next, we use modern ray-tracing software to show that the kinds of blur spots and depth-of-field limitations posited by proponents would not have arisen in Lotto’s purported projector. In Sect. 5 we consider two ancillary topics: the awkward studio rearrangement demanded by the mirror projector, and the drawbacks of lens based projectors in this case. In Sect. 6 we review the historical record, and in Sect. 7 we conclude with a judgement of the tracing theory as applied to this painting, and some speculations on the value of ray-tracing software elsewhere in the study of art.

2. HOCKNEY’S TRACING THEORY

David Hockney recently speculated that the rise in a new form of realism—which he called the “optical look”—in early Renaissance painting circa 1420, particularly in the Low Countries, was due in large part to those artists seeing, for the first time, images optically projected onto a screen.¹ It is hard, if not impossible, to test this speculation given that there is no documentary evidence from that time that Renaissance optical scientists, lens and mirror makers, patrons, subjects, or artists themselves that anyone had seen such an image of an illuminated object (specifically *not* the sun) projected onto a screen (see Sect. 6, below).⁵ There is speculation, many years and even centuries later, that indeed some Flemish artists may have seen such images. For example in 1755 Charles-Antoine Jombert (1712–1784) wrote “With regard to the darkened chamber [presumably a camera obscura] we can remark that many Flemish painters (from what it is said) have studied and imitated in their paintings the effect it presents and the manner in which it makes one see nature,” though it is unclear precisely how early is the period he is speculating about. Nonetheless, the route from such hypothesized artistic influence to visual evidence in any painting would likely be very indirect, with opportunities for numerous other influences to corrupt or overwhelm any purported optical influence. As such, rigorous image analysis would be of little value in judging the validity of this optical influence speculation.

Hockney and his collaborator, Charles Falco, make a stronger, additional claim: that some of these artists *directly used* optical devices during the execution of portions of some of their works. Specifically, they claim that some artists projected real, inverted optical images onto their supports (canvas, paper, oak panel, ...), traced them in pencil, then filled in these tracings with paint. It is this claim of artistic practice or *praxis* that can be tested through rigorous computer image analysis—the approach we follow here.

2.1 Tracing theory and *Husband and wife*

Hockney and Falco point to Lorenzo Lotto’s *Husband and wife* as the central evidence supporting the tracing theory, calling it their “Rosetta stone,”¹ which “proves” optical projections were traced. They state that it “simply is not possible” that the painting was executed without such projections. Clearly, then, if significant doubts about the theory arise for this work, the entire theory would lose a great deal of credibility.

Figure 1 shows the painting in question. The central “optical” evidence adduced by Hockney and Falco comprises:²

- two perspective breaks in the carpet pattern, specifically in the area of the keyhole
- changes in scale (“magnification”) between three portions of the keyhole
- a “blurry” or “out of focus” region at the top of the keyhole.

These authors claim this evidence arose from Lotto secretly building an optical projector, placing the table and carpet in sunlight (needed to product a sufficiently bright projected image⁶), projecting images of the tableau onto his canvas, then tracing these images in three “exposures,” which we denote **1**, **2** and **3**. (There is no evidence to distinguish the temporal order of these exposures—i.e., **1-2-3** versus **3-2-1**—but this order is irrelevant to the claims at hand.) Because such an optical system would have a limited depth of field,⁷ Hockney and Falco claim Lotto was forced to refocus his projector for the different depths in the scene, and such refocussing would induce a slight change in the magnification and in the orientation of perspective lines.²

Their explanation of the “blurry” region at the top of the keyhole is intriguing and unorthodox, and applied to no other work in the debate—indeed not even elsewhere in this painting, when it would seem applicable if their theory were right. They claim Lotto refocussed his projector for three sharp images, but painted the region at the top of the keyhole blurry to reconcile the previous blurry exposure there, **2**, with the currently sharp exposure there, **3**. Those authors give no explanation why such a “blurry” region should arise reconciling exposures **2** and **3** but not when reconciling exposures **1** and **2**.

Close inspection of the painting with magnifying glass *in situ* shows that the carpet was executed by the application of a uniform red layer of paint, with the white pattern later applied on top. A tracing on the canvas itself would thus not have been visible when the white pattern was applied. There is no visual evidence of tracing

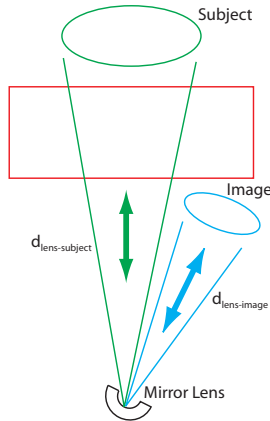


Figure 2. Optical setup proposed by Hockney and Falco to explain the image evidence in *Husband and wife*, redrawn from [2, Figure 3]. Notice that their setup does not include the canvas (screen).

in either the x-ray of the painting, or in the red layer either. Such close inspection reveals that the “blurry” portion was executed with an insufficiently fine brush—a simple non-optical explanation. Given Hockney’s claim that artists would not have painted directly under an optical projection, this visual and physical evidence is hard to reconcile with the tracing theory.

Figure 2 shows the optical setup Hockney and Falco believe Lotto used when executing *Husband and wife*. Here $d_{lens-object}$ is the object distance, $d_{lens-image}$ is the image distance, and the concave mirror is denoted “mirror lens.” Although the proponents note that their evidence could not distinguish between concave mirrors and refractive lenses, they stressed in the source book for the theory,¹ numerous popular articles,⁸ public lectures, Hockney’s BBC documentary, CBS *60 minutes*, and elsewhere that they strongly preferred concave mirrors over converging lenses.

The theory’s proponents preferred concave mirrors for a number of reasons.² First, concave mirrors produce inverted real images that preserve the left-right symmetry of the final, rightside-up image. That is, the image of right-handed subject appears right-handed in the final artwork. Such symmetry preservation thus saves the artist from the awkward and implausible chore arising from the use of a converging lens: that of filling in details of a *left*-handed drawing while viewing a *right*-handed subject. The authors even invented a term, “mirror lens,” to stress that they were describing a mirror that had the focussing power of a lens, in case art historians and the general public were not familiar with such properties:

“We discovered in the course of our research, however, that outside the scientific community, there is scant awareness of the fact that an image can be formed with a concave mirror. For this reason, we will use the term ‘mirror lens’ in this article to make explicit the imaging properties of the concave mirror.”²

We shall therefore concentrate on their preferred optical element, a concave mirror, but in Sect. 5.2 briefly analyse projectors based on converging lenses.

3. PREVIOUS IMAGE ANALYSES

If Lotto traced an exposure to the precision claimed by Hockney and Falco, i.e., 0.2%,^{2,9} then a number of image tests can be done to test their claim. Christopher W. Tyler pointed out that the perspective within a putative exposure should obey the laws of perspective and yield vanishing points (or at least approximately so, consistent with the stated 0.2% precision), just as the perspective in a photograph is correct. Tyler showed convincingly, however, that the perspective within single putative exposures in *Husband and wife* was incoherent or incorrect—deviating more from the ideal than could be explained by Hockney and Falco’s stated precision.¹⁰

There are a number of other such perspective anomalies in the carpet that argue against the use of projections. For example, the long vertical braided pattern along the right of the carpet has a slight break, roughly 1° . Hockney and Falco fit this break in their optical model and point to a change in orientation of the braided pattern across that break. However, the angular change in that braided pattern is roughly 18° , where in the optical explanation it should be much closer to 1° . In short, the visual evidence *against* the use of optics here is roughly 18 times more salient than the evidence that is, at best, consistent with the use of optics. Moreover, the breaks of 1° such as identified by Hockney and Falco appear in carpets surviving in museum collections, showing that it is quite plausible that Lotto’s carpet had such a break or that such a deviation from geometric perfection was due to the artist working by eye. Likewise, the portion of Lotto’s rug hanging in front of the table shows very large geometric anomalies and asymmetries and because it would be the same distance from a putative projector, these large anomalies cannot be due to refocusing to overcome depth-of-field limitations.

The Hockney and Falco explanation relied fundamentally upon their (unstated) assumption that the true carpet pattern was spatially symmetric, and they ascribed deviations in the painting to the refocusing of Lotto’s projector. However, these so-called “Lotto carpets” (later named for the artist) were hand-knotted by uneducated girls in the Ushak region of present-day Turkey. The vast majority of such carpets surviving in museum collections are spatially *asymmetric* to an extent equal to that found in the painting (i.e., several millimeters and several angular degrees) and the evidence is that they were asymmetric upon completion, thereby undercutting the optical explanation.¹¹ Moreover, the carpet in Lotto’s *Mystic marriage of St. Catherine and Niccolò Bonghi* (1523) is spatially asymmetric to the extent just mentioned, and since this carpet hangs vertically at the same depth from the artist (or putative projector), there would have been no refocusing. Furthermore, the asymmetries in the carpet depicted in *Mystic* are haphazard and cannot be due to the kind of optical explanation proposed by Hockney and Falco for *Husband and wife*. Indeed, even if one were to find some spatially symmetric Lotto carpets, that would not mean that the *particular* carpet in *Husband and wife* was symmetric.

In short, such carpets were generally asymmetric *upon completion*. As such, it would be inappropriate, for instance, to apply an *ex post facto* straightening transformation to a model of the carpet to justify the optical explanation, almost as if to confirm some pre-determined “conclusion.”

4. SIMULATIONS AND ABERRATION ANALYSES

As mentioned above, the optical setup proposed by Hockney and Falco, reproduced in Fig. 2 above, does not include the canvas or screen. Figure 3 shows our three-dimensional schematic of a setup that *does* include the required screen. Note that this screen imposes a severe constraint upon the optical path, forcing the light to strike the concave mirror at a large angle, greater than 15° .

4.1 Ray-tracing simulations

Figure 4 shows a schematic plan of Hockney and Falco’s optical setup, as in Fig. 2, above. The distances, focal length, aperture, and so on are the same as those given by Hockney and Falco.^{2,9} (Our figures are based on a spherical mirror—the type most easily created with Renaissance technology—but our conclusions do not change significantly if a parabolic mirror is considered instead.) Again, this figure includes no projection screen. The bottom of Fig. 4 shows the blur spots computed automatically by Zemax, where the best focus (smallest RMS blur spot for the in-focus case) was found automatically by Zemax subroutines. Notice that our simulations agree with the claims of Hockney and Falco in revealing a circle of confusion of roughly 2 mm at the rear of a putative “exposure”; if Lotto had used this (unphysical) setup, there would have been depth-of-field problems of the sort they posit.

Figure 5 shows the same information as Fig. 4, but for the realistic case where the screen is present. Notice that the minimal area blur spots (in an RMS sense) are roughly the *same size* at the two distances. First, this means that the blur spot would always be large (≈ 3 mm), larger than the detail found in the painting there and hence a poor referent for Lotto to trace. More fundamentally, though, severe astigmatism swamps any depth-of-field problems of the form central to Hockney and Falco’s optical explanation—there would have been no visual evidence or benefit provided by refocussing in the manner hypothesized by the theory’s proponents.

In short, when the full physical constraints of a purported projector are included in the analysis, the argument provided by Hockney and Falco that Lotto used an optical projector fails.

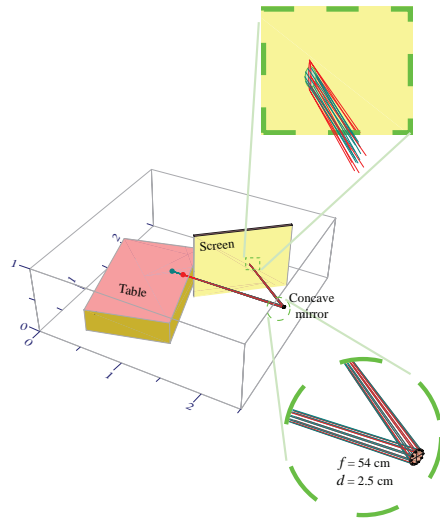


Figure 3. A rough schematic setup of a purported projector in Lotto’s studio comprising the table, concave mirror, and 116-cm-wide canvas (screen). Rays from different positions or “exposures” (distances) on the carpet are shown in red and blue; their blur spots are shown on the screen (inset). The optical parameters ($f = 54$ cm, $d = 2.5$ cm) are those given by Hockney and Falco.² Because of off-axis aberrations, there is never a sharp focus (small blur spot) nor the kind of change in spot size demanded by the projection theory (see Figs. 4 & 5, below).

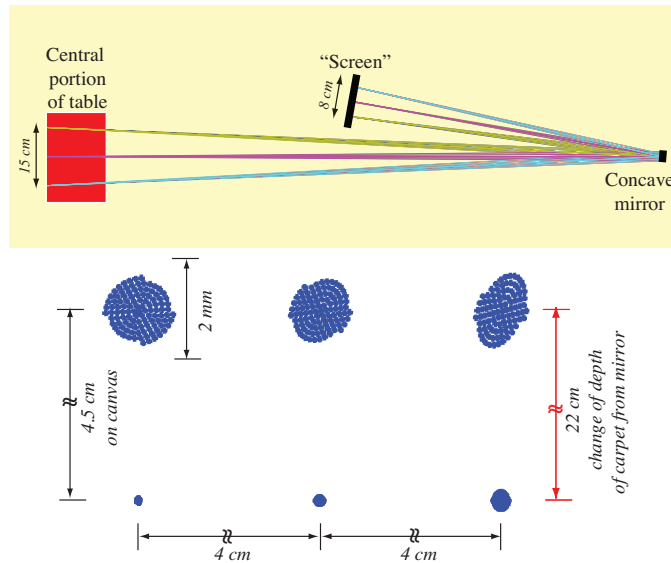


Figure 4. Top: The overhead view or *plan* of a setup based on the one given by Hockney and Falco as in Fig. 2, that is, without the canvas (screen). Bottom: The blur spots at six locations on the screen, three “near” and three “far,” separated by 15 cm on the carpet and 8 cm on a “screen,” roughly the width of the top of the keyhole. The location of the canvas was adjusted in Zemax to find the smallest RMS blur spot size for the “near” points. Indeed, the blur spots for the “far” points are large and in this (unphysical) setup would indicate limited depth of field.

5. FURTHER ANALYSES

We now turn to two ancillary matters in the optical explanation: an awkward rearrangement in Lotto’s setup, and the plausibility of an optical explanation based on a converging lens.

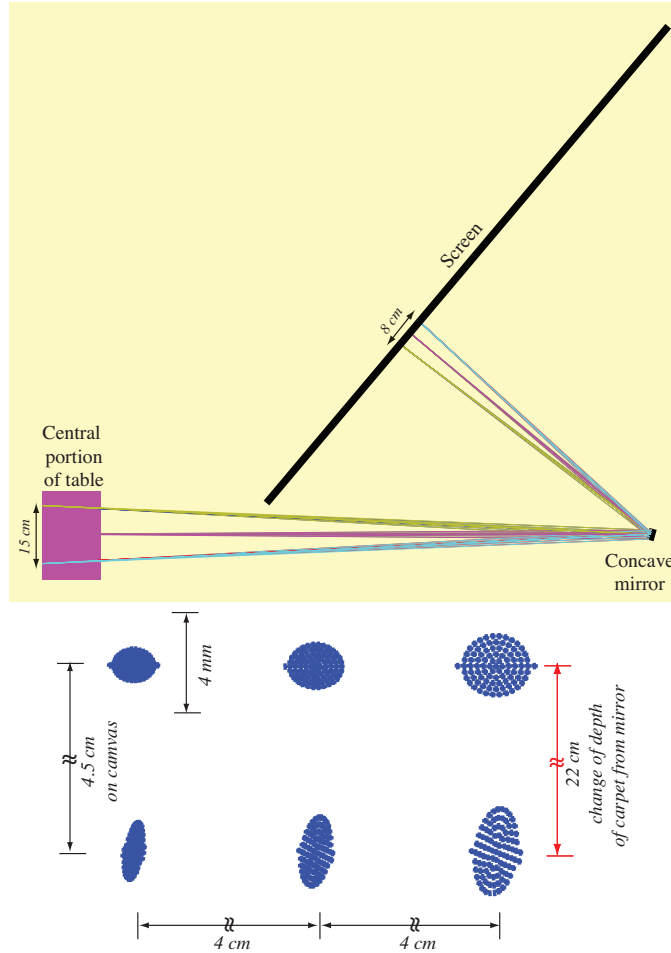


Figure 5. As in Fig. 4, the top portion shows the optical setup and the bottom portion shows six blur spots, here, though, for the realistic case where the screen is in place. Notice especially the factor of two change in spatial scale of the spots (4 mm bar versus 2 mm bar in Fig. 4). These smallest blur spots (found by Zemax routines) are roughly equally large, and likely larger than would be useful to Lotto. Most importantly, unlike in Fig. 4, here the “near” blur spots and the “far” blur spots are nearly equally large, showing that there would not have been the depth-of-field problems claimed by Hockney and Falco.

5.1 Awkward rearrangement of the setup

As shown in Sect. 4, the presence of the canvas (screen) would introduce significant off-axis aberrations, particularly astigmatism and coma, and preclude the change from in-focus to out-of-focus due to depth of field that underlies the Hockney and Falco explanation. There is, moreover, another awkward and implausible implication of the presence of the screen. Hockney and Falco point to a small change in angle along the white border pattern on the right of the carpet. The full width of the region executed under optical projection they refer to is roughly 100 cm on the table and 57 cm on the screen. If this were executed in a single “exposure” the screen would have to be at an even *larger* angle, and thus the optical angle at the concave mirror would be at minimum 18° and thus the above counter-arguments stronger still.

Given the existence of the canvas (screen), what would Lotto have to do to ensure a small point spread function across such a separation on the canvas? The above arguments show clearly that the artist could not have achieved a small point spread function in the realistic version of setup derived from the claims of Hockney and Falco. (A plane injection mirror would complicate the setup, and introduce the kinds of symmetry problems attending a single lens, described in Sect. 5.2, below.) To ensure the point spread function is as small as possible,

Lotto might have used two exposures from different sides of the canvas, but would need to rearrange his studio in an extremely awkward and implausible way.

5.2 Converging lens projector

Although Hockney and Falco are explicit in their claim that Lotto used a *concave mirror* rather than a *converging lens*, we nevertheless briefly outline the counter-argument to a lens based explanation as well. Many of the facts and rebuttals associated with the concave mirror apply with roughly equal force to a lens based claim: the lack of explicit contemporary documentary evidence for the tracing procedure, the requirement of an awkward reliance on direct sunlight illumination when depicting this indoor scene,⁶ the inherent asymmetry of Lotto carpets upon completion,¹² the fact that the white paint was applied atop the red field without any evidence of tracing, Hockney and Falco’s unorthodox explanation for the “blur” for exposures **2** and **3**, that this explanation is not applied to exposures **1** and **2** (or any other painting), and so on.

A lens would present a number of additional difficulties, however. For instance, a lens reverses the left-right symmetry of the scene; in fact this was the key drawback that led Hockney and Falco to prefer concave mirrors. While the keyhole pattern itself is approximately left-right symmetric (but not to the sub-millimeter level assumed by Hockney and Falco), the table and carpet are oriented at an angle to the line of sight and hence is quite asymmetric with respect to the view from the mirror. As such, if Lotto secretly used a lens projector, he would have had to orient the table flipped left-to-right with respect to the line of sight (i.e., tipped away at the symmetric angle). This is an awkward and implausible scenario, and would be an impediment rather than an aid to Lotto. Moreover, there is a small (16.9×21.5 cm), informal, preparatory study for *Husband and wife*, currently in the Rijksmuseum Museum—bearing grid guidelines and clearly done directly, without projections—with the orientation of the table matching that in the final painting. Thus for Lotto to have used lens projection, he would have set up his studio as it appears in the final painting, drawn the preparatory study, then altered the orientation of the table (and possibly moved it outdoors into the sunlight), then *re-oriented* it back to the original orientation to complete the painting, the orientation Hockney claims artists would have used.

Another awkward implication consequence of using a converging lens instead of a mirror would be *chromatic aberration*.⁷ Simple ray tracing of a flint glass converging lens shows that the chromatic blur spot of a lens having diameter and focal length Hockney and Falco infer would be roughly as large as those in Fig. 5, above.

6. HISTORICAL BACKGROUND

There is no documentary evidence that by the time of the execution of *Husband and wife* anyone had used a concave mirror to project an image of an illuminated object (i.e., not the sun) onto a screen and had traced it. As part of a four-day symposium to test the Hockney-Falco tracing theory^{5,13} historian Yvonne Yiu reviewed the documentary record and wrote:

“With regard to the Hockney-Falco thesis the silence of this considerable body of texts on the concave mirror projection method is deafening. Written by well-informed contemporaries who were keenly interested in the relationship between the mirror and painting and eager to impart any ‘secret knowledge’ to willing listeners, it seems inconceivable that they would not have described a method that according to Hockney and Falco revolutionized the art of their time.”¹⁴

It is thought that Lotto met the great German perspectivist Albrecht Dürer (1471–1528) near the dawn of the 16th century.¹⁵ Dürer designed, built, and documented a number of perspective machines, and wrote his four-volume **Unterweysung der Messung (Investigations into measurement)** on the problems of perspective, rendering three-dimensional scene in a two-dimensional plane, and so on. One might imagine that these artists would have discussed a topic of such mutual interest, but there is no indication of such optical methods in Dürer’s copious writings. Nor would such an absence be attributable to trade secrets. Artists and artisans of the time generally *advertised* their discoveries to attract patrons and apprentices.¹⁶ In the few cases where genuine trade secrets existed, such as the methods of Venetian glass makers, the *existence* of such secrets was widely known, even if the content of the secrets were not. We have no such documentation *about* projection “trade secrets.”

Lotto wrote a personal notebook (*Libro di Spese*), bearing notes on hiring models, travel, commissions, and so on. A short passage from the book has been used to lend support to the Hockney tracing theory for Lotto, but a careful reading of the passage, in context, suggests just the opposite. Vincent Ilardi wrote:

“In 1549 [Lorenzo Lotto] paid the enormous sum of 22 Venetian lire for a ‘big crystal mirror’ [speculum] ordered from Venice to replace a broken one while he was working in Ancona. ... In sum, these few entries in Lotto’s account book and the evidence presented above demonstrate that mirrors were used by most or many artists to project images and/or control the accuracy of their visual observations.”¹⁷

Note that...

1. This passage states that Lotto’s mirror was “large,” while the mirror Hockney and Falco infer would have been small indeed ($d \approx 2.5$ cm).
2. This passage states the cost was an “enormous sum,” whereas Hockney and Falco have repeatedly claimed that the projection mirrors were inexpensive, as would be the case for the small mirror they infer.
3. This passage states the mirror was glass (“crystal”) and breakable, while the relevant mirror would have been likely metal, and such a small metal mirror would have been unbreakable.

There is no textual evidence in the *Libro di Spese* that this mirror was *concave*, as needed for a projector, rather than plane or convex. There would seem to be no passages here that suggests that this artist had discovered what then would have been a complex optical procedure. Ilardi concludes “the evidence on the use of concave mirrors to project clear images for pictorial composition seems to be scanty or missing altogether except for the paintings themselves, as Falco has contended.” [17, pp. 199–200] It would seem, then, that all relevant physical properties that can be inferred from the *Libro di Spese* contradict those necessary for the projection claim for this painting. Finally, a thorough analysis of Italian artists’ studio practice in the Renaissance, based on a detailed reading of artisan records, bears not a single reference to the use of projection optics as a drawing aid.¹⁸

7. CONCLUSIONS AND FUTURE DIRECTIONS

We analyzed the argument and key evidence in Hockney’s optical tracing theory: Lorenzo Lotto’s *Husband and wife*, which Hockney and Falco call their “Rosetta stone.” We found that when all relevant elements are included in the setup—specifically the 116-cm-wide canvas (screen)—the light must strike the projection mirror at a large angle, and this, in turn, induces severe off-axis aberrations. The aberrations of astigmatism and coma are so large that even at the best focus, the blur spot would be larger than the visual structures in the painting and hence provide a poor (and dim) image to trace. (To reduce the size of the blur spot requires a smaller mirror, and this would make the image yet dimmer and even less useful.) Our central point, though, is that such aberrations appear from a *range* of object distances, thereby precluding the kind of depth-of-field effects central to the optical explanation. We note in passing that our rebuttal here is distinct from that for Jan van Eyck’s *Albergati portrait*, whose support is much narrower (minimizing off-axis aberrations), involves no depth-of-field issues, and involves a single line contour rather than the fine pattern detail in the Lotto carpet.¹⁹

There are a few other points which argue against the tracing theory, or at best do not support it. In brief:

1. the awkward and implausible rearrangement of the studio to change from projecting the right of the carpet to projecting the left of the carpet
2. the awkward and implausible procedure for Lotto executing a portion of the painting “blurry” in order to reconcile two sharp images projected at different times under different focus conditions (which does not occur elsewhere, i.e., in the first purported refocussing)
3. studies that show that hand-knotted “Lotto carpets” were likely spatially asymmetric *upon creation*

4. numerous perspective anomalies in the painting that cannot be attributed to the use of optics
5. geometric anomalies in other Lotto works (eg., *Mystic marriage of St. Catherine and Niccolò Bonghi*) that cannot be easily explained through the use of optics, either lens or mirror based
6. severe illumination constraints that find support in neither the painting nor Lotto's working methods, and
7. the lack of documentary support for Lotto's use of projected images as a referent for tracing, including in his private notebook (*Libro di Spese*).

7.1 Future directions

Beyond addressing the tracing theory, we believe our work provides the first application of rigorous state-of-the-art ray tracing software to address an art historical question. Our methods may be of use in studies of the other artists where an argument for the use of optical methods might be more persuasive, for example Jan Vermeer (1632–1675),²¹ Caravaggio,²² as well as those known to have used projections, such as the Venetian cityscape painter Canaletto (1697–1768), the American realist Thomas Eakins (1844–1916), and modern photorealists such as Richard Estes (b. 1932) and Robert Bechtel (b. 1932).

Ray tracing software, together with three-dimensional computer graphics models of the studio of Jan Vermeer might provide new insights into the “blurry” highlights rendered in some of his paintings, including *Girl with a red hat* (c. 1665) or *The milkmaid* (c. 1658–1660). For instance, such software might answer questions such as: Do the white spots in these painting, such as on the filials on the girl's chair or the crusty surface of the loaf of bread, correspond to the blur spots that would be produced by an optical projector such as a camera obscura *in the given studio configuration*? Or might instead the artist been *influenced indirectly* by the sight of projected blur spots in other scenes and merely added them to the painting to give an overall “optical” look or texture?

We stress, though, that the most promising avenues for computer vision and pattern recognition methods and optical ray tracing analyses in art will arise when they are strongly constrained to the art historical evidence and questions. As such, we hope the work presented here will encourage humanistic art scholars and computer and image scientists to collaborate toward identifying such questions and answering them.

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