Color and Illumination in the Hockney Theory: A Critical Evaluation

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Abstract

Recently it has been claimed that some early Renaissance painters used concave mirrors to project real inverted images onto their supports (paper, canvas, oak panel, …) which they then traced or painted over, and that this was a key source of an apparent increase in naturalism and realism in European painting around 1420. This bold theory makes implicit and explicit assumptions about the illumination and associated optical technology used for such projections. We compute and experimentally verify that the illumination requirements of the projection method are quite severe, and that in most cases subjects would have had to have been illuminated by direct sunlight, which seems unlikely for many specific paintings. We show how modern "re-enactments" of the theory's procedure in this regard are sometimes misleading or flawed, generally biased in favor of the theory. In certain versions, and for certain paintings, the theory also has testable implications for the color in final paintings. Through computer manipulation of digital images of key Renaissance paintings, we test informally whether it is faithful reproduction of *form* and *contour* or instead of *color* that best explains the naturalism in early Renaissance paintings, and conclude that it is subtleties in color. We demonstrate how the optical projection technique never aids in the accurate rendering of color, and in certain implementations severely impedes in the accurate rendering of color. Our analysis of color and illumination argues against the projection theory generally, and further supports conclusions from image analyses of specific paintings in the debate.

Introduction

In seeking to explain an apparent rise in realism in European painting evidenced in the work of Jan van Eyck, Robert Campin, Dieric Bouts, and others—a property he labelled "opticality"—the celebrated contemporary painter David Hockney recently proposed that some Renaissance painters as early as 1420 employed optical devices and their projections as aids when painting.[1,2] (Hockney later received technical assistance on his theory from expert thin-film physicist Charles Falco.) While it is well known that optical projections in camera obscuras were occasionally used by some artists in the 18th- and 19th-centuries—for instance by Canaletto (1697-1768), Joshua Reynolds (1723-92) and William Hyde Wallaston (1766-1828)—Hockney posits that such projections were used over a third of a millennium earlier, long before there is convincing documentary evidence that artists used such projections.[3] In the absence of persuasive documentary evidence, most of the debate and analyses have concentrated on the early Renaissance paintings themselves as primary evidence. While previous studies of key paintings focused on the optics of image formation and perspective (focal lengths, depth of field, vanishing points, etc.),[2,4-6] the work reported here focuses instead on color and illumination.

We begin in Sect. *I* by describing briefly the Hockney projection theory, then in Sect. *II* consider some of its implications for requirements upon illumination. Then in Sect. *III* we address the matter of color, specifically the difficulties in rendering color in the projection method. We test informally whether it is form and contour or instead color that best explains Hockney's "opticality," and explore the associated implications for the projection theory. We conclude with a summary and a few general remarks.

I. Optical Projection Theory

Hockney's optical projection theory states that some European painters as early as 1420 employed optical devices, specifically concave mirrors, to project a real inverted image of the scene or part of the scene onto a canvas or other support (paper, oak panel, etc.). According to the theory, artists would then either trace the image contours and then commit paint to the support, or perhaps even paint directly,[1,2] though Hockney admits that it is quite difficult to paint directly under optical projections. It must be noted that in the early 15th century and for over a century thereafter we have no corroborating textual documents or diagrams from artists, patrons, scientists, mirror makers, contemporary art critics or others from that time that anyone had seen a real image of an illuminated object projected onto a screen by any optical device (lens or concave mirror), much less trace or paint over it—this despite the fact that numerous other optical devices, drawing aids, books on perspective, etc., from that time are well documented.[3,7]

II. Constraints Upon Illumination

Images projected by a concave mirror (or converging lens) can be much dimmer than the original scene and this places strong constraints upon the Hockney theory. The illuminance of a projected image of a surface divided by that of the actual surface itself is expressed by the dimensionless ratio

$$R = Ar/f^2 \cos^4(\alpha) \quad (1)$$

where A is the facial area of the concave mirror (or converging lens), f its focal length, α the associated angle with respect to the mirror's principle axis and r the reflectance of the mirror surface ($0 \leq r \leq 1$).[8] Measurements of surviving mirrors from the 15th century suggest reflectances of approximately $r \sim 0.5$.[7] The spatial average of $\cos^4(\alpha)$ over a typical field of view is roughly 0.5. For the mirror putatively used for a projection in Lorenzo Lotto's "Husband and wife" (1523), Hockney and Falco infer $f = 54$ cm and diameter = 2.4 cm.[2] Together with an assumed reflectance of $r \sim 0.5$, this implies $R \sim 0.00078$. For other plausible optical devices this ratio is typically of this order, $R \sim 1/1000$, which corresponds to $\log_2 1000 \sim 10$ f-stops.[9] (We mention too that if the projection is onto a darkened canvas or ground, as in the Italian Baroque master Caravaggio's works,[10] the illumination constraints are even more severe.) To put this reduction in illuminance in context, consider the fact that commercial sunglasses have a transmittance of approximately 10%. The typical reduction in the illuminance through relevant projection corresponds, then, to wearing three pairs of sunglasses, stacked one in front of the other. Even with dark adaptation, few if any artificial illuminants available in Renaissance Europe (candles, oil lamps, …) provide illumination to yield projected images that are adequately visible; direct sunlight seems to be the required illuminant.

We experimentally verified Eq. 1 for a large modern concave shaving mirror (A = 80 cm^2, f = 70 cm, $r \sim 0.9$) using a standard photographic light meter and an outdoor scene projected onto a white screen in a dark room. While Eq. 1 predicted a difference of 6 f-stops, we found 6.5 ± 0.5 f-stops—excellent agreement, the difference attributable to the reflectance of the paper.

What could be the source of illumination in paintings Hockney claims were made under projection? Consider first the works of Michelangelo Merisi, better known as Caravaggio (1573-1610). Hockney himself attests that Caravaggio "...worked in dark rooms—cellars—very common in those days... He used artificial lighting".[1] Likewise, G. P. Bellori, Caravaggio's biographer, wrote in 1672: "He never showed any of his figures in open daylight, but instead found a way to place them in the darkness of a closed room, placing a lamp high so that the light would fall straight down..." Joachim von Sandrart wrote in 1675: "He used dark vaults or other shadowed rooms with one small light (*liecht*) above, so that the light falling on the model made strong shadows in the darkness..."

If Caravaggio worked by artificial lighting and (as claimed by Hockney) employed optical projections, how many candles or oil lamps would he have needed? Consider Caravaggio's "Supper at Emmaus" (1601-2), a painting Hockney claims was painted at least in part under optical projections.[1] We formed a very rough recreation of Caravaggio's "Emmaus" studio, with table, accoutrements and four models. We waited 10 minutes in the dark to become dark adapted, and then added candles, off to the side, one by one until the scene was just bright enough to see well enough to draw or paint by standard methods—roughly five candles. But of course, as given by Eq. 1, a projection of this scene would be far too dim to see or trace over. To obtain the required brightness in the projection using a typical optical system such as Hockney and Falco describe (R ~ 500), Eq. 1 implies that the scene would have to be illuminated by over two thousand candles or several dozen oil lamps. Such a large number of light sources would necessarily yield diffuse illumination and preclude the sharp shadows that empower Caravaggio's art in general and "Supper at Emmaus" in particular.

Of course the above analysis is very rough; nevertheless, it is clear that even if a mirror with somewhat lower f-number was used, a large number of artificial light sources would be needed—a number hard to reconcile with visual evidence within the painting.

Perhaps Caravaggio used direct sunlight (which would provide sufficient illumination for projections), despite Hockney's own claim and that of art historians over centuries to the contrary. Consider Caravaggio's "Death of the Virgin" (1605), shown in Fig. 1. While upon initial impression the viewer might believe that direct sunlight provided the illumination, a more careful analysis suggests otherwise. First, consider the matter of the size of the illuminated area. There would be diurnal and even annual change in angle of solar illumination over the many hours and months Caravaggio worked on a typical painting.[10] It is unlikely that an enormous plane mirror was used to track the sun, much as in solar collectors, because at the turn of the 17th century plane mirrors were very expensive, costing more than master paintings of equal area.[7] (Nor was such a mirror in his estate.) We can imagine that a large diffuse surface such as a sunlit wall provided the illumination, but such a surface would yield diffuse shadows, not the sharp ones that pervade the painting.

Even more revealing is the illumination of the ceiling at the upper left of "Death"; sunlight *never* illuminates a ceiling directly. Solar illumination of a ceiling requires a reflection—from a water surface or horizontal mirror, say—which would yield a region of double intensity on the rear wall where the direct and reflected illumination overlapped. We find no such doubly-illuminated region on the rear wall in that painting. Similar analyses of Caravaggio's "Calling of St. Matthew" (1599-1600) reveal shadow lines directed *upward*, likewise strongly suggesting that a local (artificial) light source was the illuminant, not sunlight.

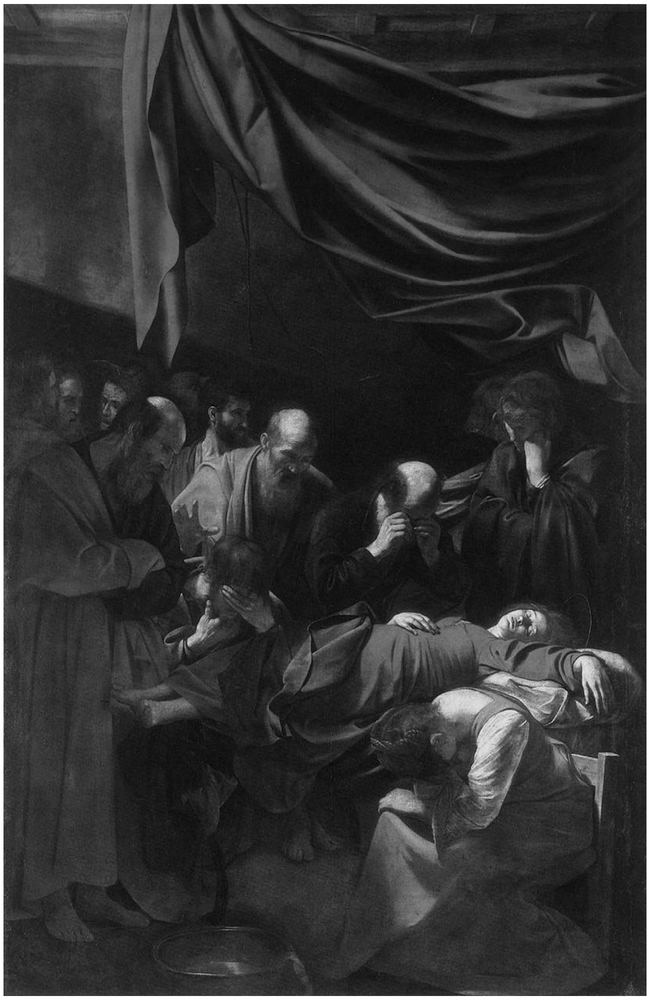

Figure 1. Caravaggio, "Death of the Virgin" (1605), oil on canvas, 369 x 245 cm, © Museé du Louvre. The illumination of the ceiling and large area suggest that the source is not the sun.

We note that self portraits, such as Caravaggio's "Self-portrait as sick Bacchus" (1593), cannot be made by projections because the sitter-artist must be illuminated by bright light while the nearby canvas is in deep shadow; as the artist turns to trace his projected image, the image moves, and so on. Given that we can be sure that "Self-portrait as sick Bacchus" was not created using projections, explanatory simplicity or Occam's razor suggests that neither were similar paintings, e.g., "Bacchus" (c. 1596).[5]

Together these analyses suggest that Caravaggio did not use direct sunlight as the illumination (in agreement with art historical scholarship over centuries) and strongly argue against the Hockney theory, at least for Caravaggio.

There are, admittedly, a number of awkward or ad hoc methods that could rely on optical projections, but these seem unlikely to have provided any benefit to Caravaggio. For instance, he might have arranged the models outdoors in direct sunlight and used a projection to capture outlines, and then completed the painting under artificial illumination, presumably indoors, deliberately obscuring some of the visual evidence of the previous processes. To take such alternatives seriously we would have to reject Hockney's urgings to view the painting itself as "primary evidence" and to overlook the challenges Caravaggio would have faced altering his composition during his months of work.

Hockney has performed a number of putative "re-enactments" of the optical projection method, but some of these are misleading in a number of ways, generally making the projection theory seem more plausible. For instance, he has used high-power theatrical stage lights with Fresnel lenses, which provide highly controlled, directional, stable and extremely bright illumination; these have no counterpart in the Renaissance. A misleading scene in this regard arose from his BBC documentary. Mr. Hockney states that natural light from a northern window is sufficient for the projection method. (Artists have long favored indirect northern illumination because it is diffuse and stable, both in intensity and color temperature.) In fact, however, Hockney demonstrates a projection of a *sunlit* outdoor building *viewed through a northern window—not* that skylight through a northern window is sufficient for projections. Furthermore, in this scene he uses a concave (apparently *parabolic*) mirror with roughly an order of magnitude greater area, and thus light collecting ability, than the mirrors he, Falco and others compute.[2,4,5]

III. Color in the Hockney Theory

Central to Hockney's theory is the notion of a painting's "opticality," a somewhat loose term by which he means "photographic looking," very realistic and natural.[1] He believes that many paintings that possess such "opticality" were indeed made using optical projections—in his phrase, such paintings *appear* "optical" because they *are* "optical." While it is difficult to make a precise or quantitative definition of the term, Hockney is clear on which paintings possess this property, and which do not. Examples of those that do include Jan van Eyck's "Portrait of Arnolfini and his wife" (1434); Lenoardo da Vinci's "Ginevra di Benci" (c. 1480), "Mona Lisa (La Gioconda)" (1503-5), and "Madonna of the Rocks" (1495-1508); as well as Robert Campin's "A Man" (c. 1430), "A Woman" (c. 1430), and "The Merode Altarpiece" (c. 1425).[1] Representative paintings that *lack* "opticality" generally have a smaller range of lightness and saturation, and accordingly seem somewhat flatter, as for instance virtually all Medieval European paintings and Renaissance works such as Albrecht Dürer's "Portrait of Oswolt Krel" (1499). Apparently "opticality" may involve—but surely is not limited to—*chiaroscura* (Italian, "light-dark") the use of exaggerated contrasts of light and dark, as in Georges de la Tour's "The Dice Players" (1649-51), *sfumato* ("hazy" or "smoky" style), as in Leonardo's "Mona Lisa (La Gioconda)" (1503-5), and subtle color gradations.

Tracing images through Hockney's optical projection technique never aids in the accurate rendition of color, any more than the outlines in a child's coloring book materially aid in the rendering of subtle color. Moreover, if an artist attempts to paint directly under projections, his ability is impeded significantly. Suppose an artist sees a colored projection on a white canvas, say the red image of an apple. What color pigment should the artist apply in order to make the painted apple appear to him in the proper color? Red? No… *white*!—like a movie screen. The cognitive "force," so to speak, is to make the painter apply low-saturated paints, ones that tend to decrease the "opticality" of the resulting image (see below).

It is extremely difficult to paint under optical projection and achieve accurate color when the painting is to be subsequently viewed under normal (neutral) illumination. Under projection, the perceived color depends in extremely complex ways upon both additive color mixture processes (associated with the colored illuminant) and subtractive color mixture processes (associated with the light reflecting from the pigment).[9] There are, furthermore, a number of phenomena in human color perception that make rendering color under the dim projections difficult, such as the Purkinje shift where the perceived lightness of red and blue regions changes as the overall illumination is reduced.[11]

Figure 2 explores in an informal way the relative importance of color and contour to "opticality." The top figure is Leonardo's portrait "Ginevra di Benci" (c. 1480). The middle figure shows the original altered in software to distort its shape, but not its color, i.e., it has the contours wrong. Most impartial viewers would agree that this version still appears "optical" in Hockney's sense. The bottom figure shows the original altered in software to distort its color, but not its shape, as might result had Leonardo attempted to paint under projections, as discussed above (without subsequent correction). The colors were adjusted in software to be less saturated, and the subtle variations in lightness are reduced. Most impartial viewers would agree that this version appears less "optical" than both the original and the deformed versions. Similar demonstrations with a portrait detail from Dieric Bouts' "Altarpiece of the Holy Sacrament" (1464-7) and Robert Campin's "A Woman" (c. 1430) reinforce these conclusions.

Conversely, we can artificially "opticalize" digital images of paintings Hockney classifies as non-optical by the inverse process, increasing saturation and expanding the lightness range in a way consistent with known additive and subtractive color mixture. For instance, such an artificially "opticalized" version of Albrecht Dürer's "Portrait of Oswolt Krel" (1499) appears three-dimensional and "photographic."

Figure 2. Top: Leonardo da Vinci, "Genevra di Benci" (c. 1480), oil on panel, 38.4 x 36.8 cm, © Board of Trustees, National Gallery of Art. Middle: The image is distorted to simulate random, inaccurate tracings. Bottom: The image is adjusted to simulate color changes associated with painting under optical projection (lower saturation, restricted palette).

It is clear we are not revisiting the late 16th-century Renaissance debate of whether form or color—*disegno* contra *colore*—was more essential to great art. Disegno refered first and foremost to large-scale composition or design, not the accurate rendering of shape. Instead, the above discussion addresses the relative contribution of accurate shape rendering and accurate color rendering to Hockney's more limited concept of "opticality," the matter at hand when we discuss the possibility of projections.

From these and related experiments and analyses we conclude that getting contours correct (which is facilitated by the projection method) has little impact upon the "opticality" of the resulting painting, and that getting color correct (which is *not* facilitated by the projection method) is a more important correlate of "opticality." In short, putative optical projections seem not to enhance significantly a Renaissance artist's ability to make an "optical" painting. Other sources, for instance the beginnings of the use of oil paint around this time, surely play a role.[5,12] Oil paints afford a greater range in lightness and saturation than previous media such as egg tempera. Furthermore, new colors such as tin-lead-oxide yellow (massicot) arose as did subtle glazing techniques. Most importantly, oil paint dries much more slowly, allowing artists to mix colors on the support, and to make many alterations and revisions.

Conclusions

We provided a quantitative and experimental analysis of the illumination constraints attending Hockney's projection theory. These constraints are severe; generally speaking solar illumination is needed. Shadow analysis of Caravaggio's and some other paintings argues against such solar illumination. Accurate rendering of color is never helped by the projection method, and if an artist attempts to paint directly under projection, color rendition is impeded significantly.

While our results cast strong doubt upon the Hockney theory, at least as far as illumination and color are concerned and for the paintings discussed, we do not claim to have "disproven" the theory. But we do not need to do so. The burden of proof for the theory lies squarely on the shoulders of the revisionists Hockney and Falco. Their methodological challenge is not to show that the projection theory is consistent with optical evidence, or even fits it superbly (and is consistent with associated historical facts). Instead, their challenge is to show that other, traditional explanations are incompatible with such evidence, or otherwise implausible.

They have yet to rise to that challenge.[13]

Acknowledgements

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Biography

David G. Stork is Chief Scientist of Ricoh Innovations and Consulting Professor of Electrical Engineering and Visiting Lecturer in Art History at Stanford University. His physics degrees are from the Massachusetts Institute of Technology and the University of Maryland and he has been on the faculties of Wellesley College, Swarthmore College, Clark U., Boston U. and Stanford U. and was Artist-in-Residence through the New York State Council of the Arts. He has published in physiological optics, color, color vision, pattern classification, machine learning and concurrency theory. His five books include *Seeing the Light: Optics in nature, photography, color, vision and holography*, and *Pattern Classification* (2nd ed.). He was creator of the PBS television documentary "2001: HAL's Legacy," based on his book *HAL's Legacy: 2001's computer as dream and reality* (MIT).