Computer analysis of lighting style in fine art: Steps towards inter-artist studies

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ABSTRACT

Stylometry in visual art—the mathematical description of artists' styles—has been based on a number of properties of works, such as color, brush stroke shape, visual texture, and measures of contours' curvatures. We introduce the concept of quantitative measures of lighting, such as statistical descriptions of spatial coherence, diffuseness, and so forth, as properties of artistic style. Some artists of the high Renaissance, such as Leonardo, worked from nature and strove to render illumination "faithfully"; photorealists, such as Richard Estes, worked from photographs and duplicated the "physics based" lighting accurately. As such, each had different motivations, methodologies, stagings, and "accuracies" in rendering lighting clues. Perceptual studies show that observers are poor judges of properties of lighting in photographs such as consistency (and thus by extension in paintings as well); computer methods such as rigorous cast-shadow analysis, occluding-contour analysis and spherical harmonic based estimation of light fields can be quite accurate. For this reasons, computer lighting analysis can provide a new tools for art historical studies. We review lighting analysis in paintings such as Vermeer's *Girl with a pearl earring*, de la Tour's *Christ in the carpenter's studio*, Caravaggio's *Magdalen with the smoking flame* and *Calling of St. Matthew*) and extend our corpus to works where lighting coherence is of interest to art historians, such as Caravaggio's *Adoration of the Shepherds* or *Nativity* (1609) in the Capuchin church of Santa Maria degli Angeli. Our measure of lighting coherence may help reveal the working methods of some artists and in diachronic studies of individual artists. We speculate on artists and art historical questions that may ultimately profit from future refinements to these new computational tools.

Keywords: lighting analysis, art analysis, occluding-contour algorithm, spherical harmonic lighting analysis, Caravaggio, *Adoration of the Shepherds*, Baroque art, Vermeer, *Girl with a pearl earring*

1. INTRODUCTION

Connoisseurs and other art scholars have long sought to specify aspects of artists' styles for identifying artists, for authenticating works, for diachronic studies of artistic development, for making aesthetic distinctions, and other scholarly tasks. To this end, formalists such as Giovanni Morelli (1816–1891) and Bernard Berenson (1865–1959) codified brush strokes, color palettes, iconography and details in portraits, such as style in rendering of ears, fingers, and fingernails.[1] While connoisseurship fell out of favor starting in the 1970s, particularly in the academy,[2] a number of cultural and professional developments have led to a revitalization of connoisseurship.[3] One such development is the application of rigorous computer vision to problems in the history and interpretation of art,[4,5] including the quantification of style.[6,7] Although rigorous image-based lighting analysis has been used to answer debates in art studies—such as the rebuttal of claims that some artists as early as 1430 secretly traced optically projected images[8]—rigorous lighting has not been used in inter-artist studies of style. Our preliminary study here introduces the application of rigorous computer vision to the problem of quantification of lighting as a component of style.[9]

Section 2 briefly describes a number of lighting analysis techniques that have found use in studies of fine art, the assumptions underlying them, their validity and range of applicability. Section 3 describes how these techniques can be used to characterize artists' lighting styles. Section 4 summarizes our conclusions and points to future application of these techniques.

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2. LIGHTING ESTIMATION TECHNIQUES

The general characterization of lighting we shall consider includes the number and placement of sources, their relative intensities, and their spatial distribution.[10] Here we shall concentrate on works in oil on canvas, and defer consideration of other media such as gesso, egg tempera, or prints such as intaglio, serigraph, and monoprint, as well as considerations of color or chromatic effects.

2.1 Cast-shadow analysis

Perhaps the simplest method of estimating lighting direction is cast-shadow analysis.[11–13] If the source has a fairly small angular extent, such as the sun or a candle, one merely identifies a point on a cast shadow and its corresponding point on the occluder and draws a line between them. This line, extended, should pass through the source, even if it is outside the picture frame. Several such lines, in general position, will intersect at the location of the light. The information gleaned is the position or direction in the plane of the painting—not in front or behind the plane of the painting. Of course, does not work with *attached* or *form* shadows.[10,11] Simple cast-shadow analysis confirms that the light source is at the location of the oil lamps or candles in works such as Joseph Wright of Derby's *An experiment on a bird in the air pump* (1768), Gerrit van Honthorst's *The matchmaker* (1625), Georges de la Tour's *Christ in the carpenter's studio* (c. 1645) and *Magdalen with the smoking flame* (ca. 1638–43). Note that some artists, such as Vincent van Gogh, rarely painted cast shadows for their figures.

If an illumination source is small and distant, then the transition from a full shadow or *umbra* to an illuminated area is sharp; if the source is broad and close, that transition is gradual, admitting a partial shadow or *penumbra*. As such, the presence and extent of penumbrae can help distinguish the lighting styles of different painters. For instance, the upward-slanting cast shadow in the upper-right corner of Caravaggio's *The calling of St. Matthew* reveals a penumbra somewhat larger than do other cast shadows, and this may indicate that the illumination source was the sun and the occluder was a distant portion of Caravaggio's studio roof.[14]

2.2 Highlight analysis

If we know or can confidently assume the three-dimensional form of an object that has a specular or mirror-like reflection or highlight, we can infer the direction of illumination based on the position of that highlight. Spheres are among the simplest objects for such analysis (Fig. 1),[15] and spheres appear as bubbles, glass globes, shiny map globes, and so on in a number of paintings such as Jean Baptiste-Siméon Chardin's *The soap bubble* (c. 1739) and Johannes Vermeer's *Allegory of faith* (ca. 1670–72).

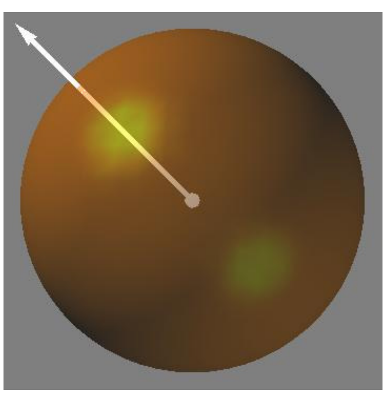

Figure 1. The highlights on an illuminated sphere can be used to infer the two-dimensional direction to the illumination. The computer model here shows a partially transparent sphere illuminated by a point source. The highlight at the upper-left is from the outer surface at the front while the highlight at the lower-right is from the inner surface at the rear. A straight line from the center of the sphere through the center of the highlights shows the direction to the illuminant. Although such highlights can be used to infer the direction in the full 4π steradian of directions, in art historical practice, however, such highlights are most often used to estimate the 2π radian (360°) of directions in the plane perpendicular to the line of sight.

Likewise, highlights in eyes can be used to infer the direction of illumination;[16] such highlights appear in Vermeer's *Girl with a pearl earring*,[13] Jean-Auguste-Dominique Ingres' *Portrait of Joseph-Antoine Moltedo* (c. 1810) and Chuck Close's hyper-realist portraits and many other realist portraits. An eye is not a perfect sphere, of course, but has a corneal bump. If an artist depicts reflections or highlights from an eye, it is generally the brightest or first of the four Purkinje images—the one off the outer cornea. [15, p. 149] The orientations of the corneal bump must be estimated in order to estimate the direction to the illumination source. This corneal orientation is found by fitting an oval to the iris or colored part of the eye. The orientation of the principle axis and minor axis reveals the overall direction of gaze perpendicular to our line of sight; the eccentricity of the best fit oval reveals the angle of gaze away from the viewer, as shown schematically in Figs. 2 and 3. Previous methods of gaze angle estimation (in video) were based on just the single outer boundary of the iris, which in video images is easier and more accurately detected than the inner contour.[17] Once the orientation of the cornea and the geometric center of the highlight have been estimated, it is a simple matter of geometric optics to infer the direction of illumination.[16] (In some cases, estimates from two eyes are accurate enough to can be used to infer the distance of the source, by triangulation.)

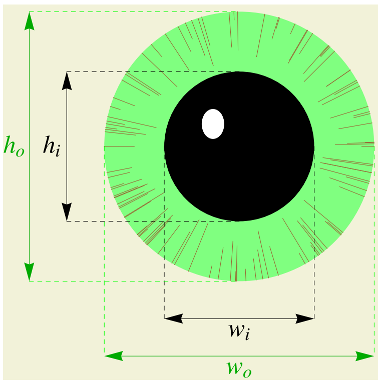

Figure 2. The direction of gaze can be estimated by fitting an oval to the boundary of the pupil, and the boundary of the iris, yielding inner width and height w_i and h_i and outer width and height w_o and h_o. For gaze angles in the horizontal direction, the angle of gaze can be computed by Eq. 1. For the case shown here, the pupil is a circle, so the direction of gaze is directly toward the viewer, or artist—that is, $\theta = 0°$.

The gaze angle, or orientation of the corneal bump, is specified as the angle θ with respect to the direction toward the viewer (or artist), and can be estimated by the geometry of the iris, specifically:

$$\cos\theta = \frac{1}{2}\left(\frac{w_i}{h_i} + \frac{w_o}{h_o}\right) \quad \text{or} \quad \theta = \cos^{-1}\left(\frac{w_i h_o + w_o h_i}{2 h_i h_o}\right). \tag{1}$$

Equation 1 is ambiguous as to whether the angle is positive or negative (e.g., rightward looking or leftward looking), but in practice that is rarely if ever ambiguous in the painting, and the scholar can impose, by hand, the sign of the gaze angle.

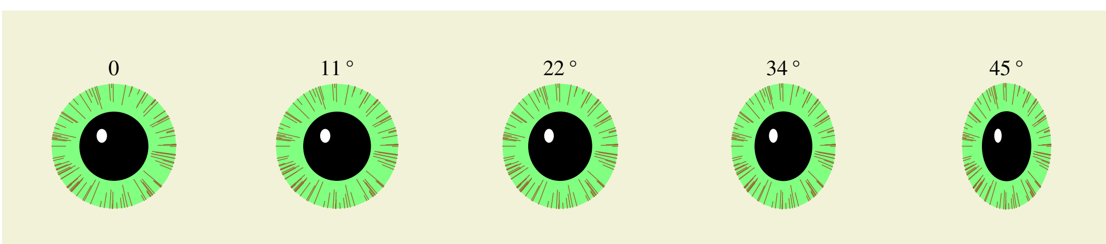

Figure 3. The orientation of the eye, shown here for various angles in the horizontal plane, can be estimated from the dimensions of the ovals fitting the inner and outer contour of the iris by means of Eq. 1.

2.3 Planar surface

Another special case that admits simple analytic solution is that of a diffusely planar surface (possibly with a specular reflection component) illuminated by a point source such as a candle (Fig. 4). Such surfaces appear in many realist paintings, for instance as floors, tabletops or walls. Kale and Stork derived the forward appearance model for such a "weak model" case and presented an iterative algorithm for inferring the location of a point source illuminating that surface, its reflectivity or albedo, and its angle of inclination away from the viewer.[18,19] They used this method to show that the lighting on the floor in Georges de la Tour's *Christ in the carpenter's studio* was better explained by a source in place of the depicted *candle* than "outside the picture" or "in place of the other figure," as was claimed by Hockney.[8] Their results confirmed the results of cast-shadow analysis (Sect. 2.1), occluding-contour analysis (Sect. 2.4), and computer graphics (Sect. 2.7) rebutting Hockney's claim that de la Tour executed this painting by tracing an optically projected image.[20]

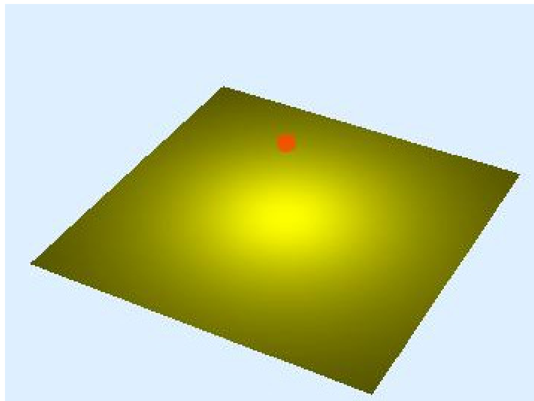

Figure 4. The location of a single point source can be estimated from the pattern of brightness on a Lambertian or diffusely reflecting surface. Three parameters (height of the source, albedo or reflectivity of the surface, and tip angle of the surface) are all estimated so as to minimize the squared difference between the model and the measured intensities over the surface.

These methods can be extended to include nonlinear lighting rendering (modeled as a gamma exponential transformation), surface reflectances of various specularity, and so forth.[21]

2.4 Occluding-contour analysis

The pattern of brightness along the outer boundary or *occluding contour* of an object contains a great deal of information about the illumination. If the surface is Lambertian (diffusely reflecting) and of uniform albedo, a number of methods can be used to infer properties of the illumination from the contour. If the illumination is parallel, for instance from a distant point source, then a very simple method can be used to infer the direction. One merely finds the brightest portion of the contour; the illumination is along a line perpendicular to that portion of the occluding contour.

The occluding-contour algorithm is a more reliable and robust model-independent method for estimating the direction to a distant small source based on the pattern of light intensity along the occluding contour of an object.[10,22–24] The method is valid if the source is fairly small and distant, so that the illumination direction is nearly the same for each point along the contour. (The method is applicable even if there is an additional overall ambient illumination.) In brief, the method finds the direction of illumination that best explains the measured brightness along the contour (in a sum-squared error sense). This method was developed for forensic analysis of photographs to detect tampering,[23] but has been used to estimate the location of illumination sources in paintings by Caravaggio, de la Tour, Vermeer, and others.[10,11,13,19,24,25] The occluding-contour algorithm can be considered a limiting case of complex light field analysis, which we explain in greater detail immediately below.

2.5 Complex light field analysis

Occluding-contour analysis is appropriate in realist works if the light source is small and distant. However, most tableaus in realist fine art are illuminated by complex distributions of sources, such as windows, candles, the sun, and so on. As with simple occluding-contour analysis, in complex light field analysis the rendered surface in question must be Lambertian and of uniform lightness or albedo along the contour being analyzed. Only convex objects can be used to analyze the illumination by this method. If an object is con*cave*, light can scatter from one surface onto another surface, severely complicating the analysis. For the same reason, objects must be reasonably well separated for the analysis to give meaningful answers; if the objects are too close together, light can scatter from one object to another, severely complicating the analysis.

We let $\mathbf{n}$ denote a unit normal at a point on an occluding contour, $\mathbf{v}$ a unit vector in an arbitrary direction, and $L(\mathbf{v})$ the non-negative intensity of the light incident from that direction. Thus the brightness at the surface of an object is based on its reflectance function, $R(\mathbf{v}, \mathbf{n})$, according to

$$E(\mathbf{n}) = \int_{\Omega} L(\mathbf{v}) R(\mathbf{v}, \mathbf{n}) d\Omega, \tag{2}$$

where $d\Omega$ is a differential area, which can be considered on a bounding sphere. We use $R(\mathbf{v}, \mathbf{n}) = \max[\mathbf{v}^t \mathbf{n}, 0]$, the clamped Lambertian reflectance function. We can express the brightness function in Eq. 2 as a sum over the orthogonal complete set of real spherical harmonics,

$$L(\mathbf{v}) = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} l_{n,m} Y_n^m(\mathbf{v}), \tag{3}$$

where each $Y_n^m(\cdot)$ is the m^{th} spherical harmonic of order n, and the $l_{n,m}$ are the coefficients describing the particular lighting environment. We assume the "camera function"—the pixel- or point-wise mapping of luminance detected on the object to final image—is linear. (Non-linear extensions can be accommodated. [16, Appendix B]) In our linear case, then, we have $I(\mathbf{x}) = E(\mathbf{n}(\mathbf{x}))$, where $\mathbf{x}$ is the position in the image. Figure 5 shows the illumination pattern corresponding to real spherical harmonic functions. The figures on shaded background are the bases for viewing along the z axis, and used to characterize the illumination, as described by Eq. 4, below.

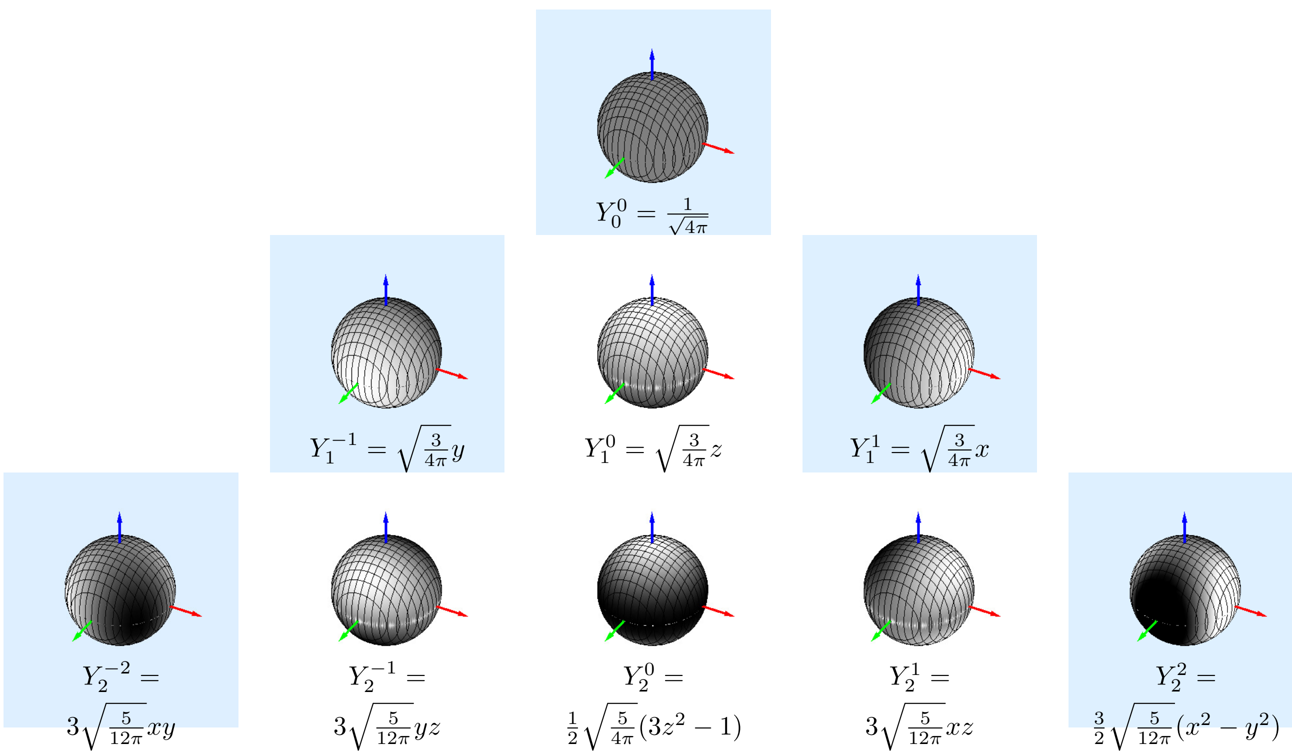

Figure 5. Real spherical harmonics provide a basis set for describing the incident light incident upon an object or scene. Here, the first nine basis functions, Y_m^n are shown unnormalized, for clarity The axes are x (red), y (green) and z (blue). The functions highlighted in light blue background are independent of z, and are used in Eq. 4.

The above derivation is very general and applies to an arbitrary point on a three-dimensional surface. If we restrict consideration to the occluding contour of an object, the normal vector is perpendicular to the viewing direction and this limits the set of spherical harmonics we need consider. Further, although this set is in principle infinite, in practical applications five coefficients suffice to reveal differences in lighting. The (truncated) representation of the brightness profile along an occluding contour then becomes:

$$I(\mathbf{x}) = l_{0,0}Y_0^0 + l_{1,-1}\frac{2\pi}{3}Y_1^{-1}(\mathbf{n}) + l_{1,1}\frac{2\pi}{3}Y_1^1(\mathbf{n}) + l_{2,-2}\frac{\pi}{4}Y_2^{-2}(\mathbf{n}) + l_{2,2}\frac{\pi}{4}Y_2^2(\mathbf{n}), \tag{4}$$

where the $l_{n,m}$ are the coefficients and the $Y_n^m(\cdot)$ depend only on the x and y components of the surface normal. These five coefficients (expressed as a vector $\mathbf{w}$) are then estimated so as to minimize a mean-square error measure between the forward model explanation of the intensities and the actual measured intensities, all along the occluding contour of an object.[26] Figure 6 shows the brightness along four contours in Caravaggio's *Nativity* and the model fits as well as the primary direction of illumination as estimated from the various signatures.

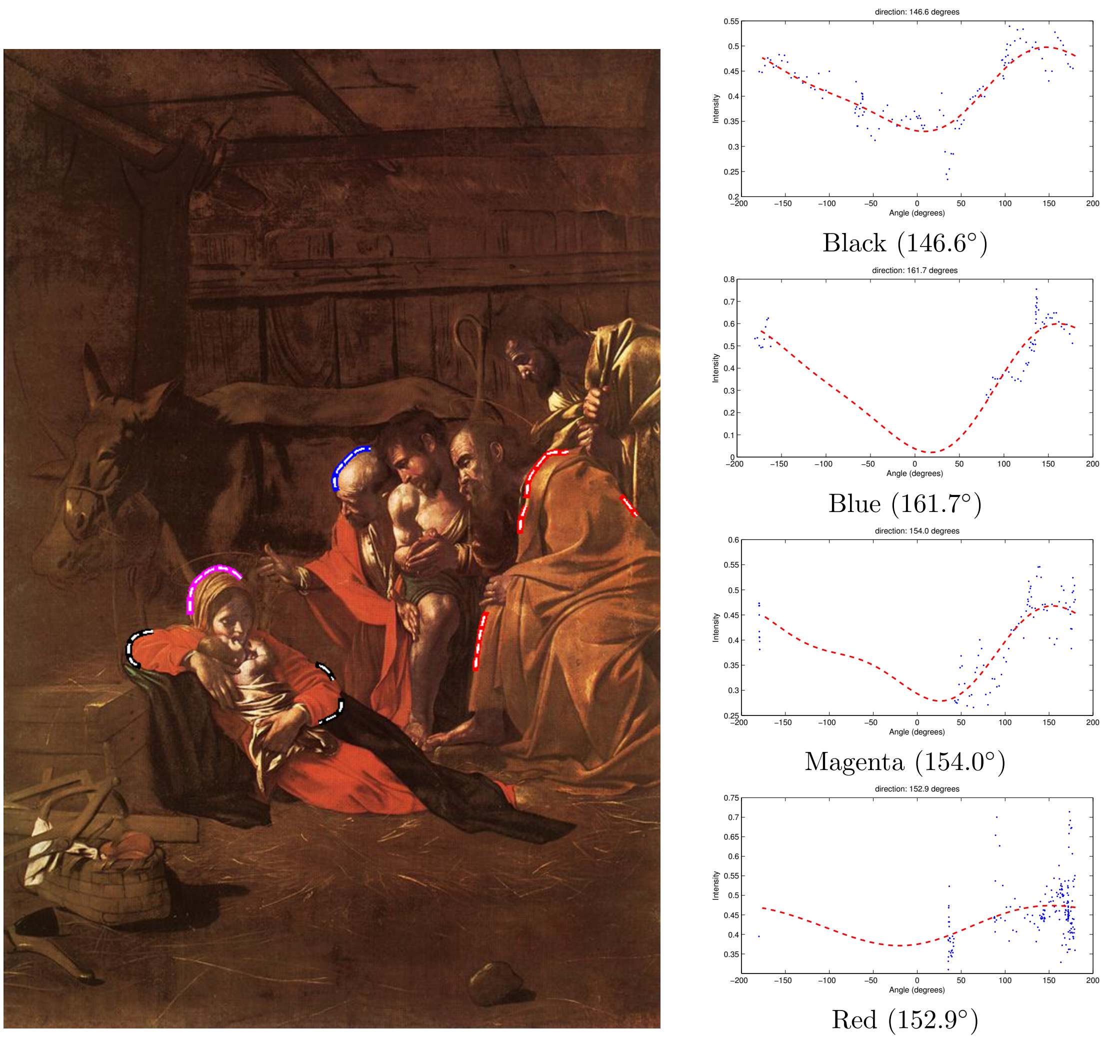

Figure 6. A complex lighting analysis of Caravaggio's *Nativity* shows four color-coded sets of contours. The measured intensities versus angle are shown in the graphs at the right. The red dashed curves are derived from the best mean-squared error model fits of the $l_{m,n}$ coefficients in Eq. 4. These computer methods may be superior to informal methods for estimating the direction of illumination in such works, such as those given "by eye" for works of Caravaggio by Grundy and Lapucci to search for variations in lighting direction they attribute to the artist secretly using an optical projector.[27]

This lighting estimation method was developed for detecting tampering in digital photographs. If the lighting signature from one object in a digital photograph, $\mathbf{w}_A$, differs significantly from that of another object, $\mathbf{w}_B$, this difference strongly suggests that one of those objects was spliced into the photograph. Stork and Johnson this method to detect the painterly analogy to such "tampering" in the portraits of Garth Herrick.[28] Herrick works from two photographic referents—one of the figure taken under one lighting condition, another of the desired background taken under a likely different lighting condition. Objects in the such final paintings may—and generally do—differ in their lighting signatures. Even differences difficult to discern by eye can be detected by these computer methods just described.

2.6 Lighting estimation using shape-from-shading

The subdiscipline of computer vision known as *shape from shading* addresses the problem of recovering the three-dimensional shape of objects within a scene based solely upon a single two-dimensional grayscale image of that scene.[29] One can use these algorithms "backward" as well: assume a three-dimensional model and infer the direction of illumination. Shape-from-shading methods are rather subtle and require care in their practical application. They can be useful for inferring simple illumination fields, such as from a single or small number of localized sources, but can become computationally unstable under complex lighting conditions. Johnson and his colleagues used this method to estimate the direction of illumination in Johannes Vermeer's *Girl with a pearl earring.*[13] The agreement between the direction estimated by shape from shading and five other methods in this tronie (or character study) strongly suggest Vermeer worked from actual figure in his studio, not (as some art scholars maintained), an imagined figure.

2.7 Computer graphics

Computer graphics reconstructions of studios have been used to explore artists' working methods or praxis, primarily for geometry. For instance a reconstruction of the tableau in Johannes van Eyck's *Portrait of Giovanni (?) Arnolfini and his wife* to explore geometric relations to address the claim that this work was executed under optical projections,[30,31] Other geometric work includes Hans Menling's *Virgin and Child and Maarten Nieuwenhove* diptych,[32] Diego Velãzquez's *Las meninas*,[33] among others.

Computer graphics based studies of illumination in realist art generally require the construction of the full tableau, or *tableaux virtuel*, based primarily on matching the geometry in the artwork, all while obeying physical constraints such as occlusion, surface contact support, and so on. Then the scholar adjusts the virtual illuminants, and possibly physical properties such as the bi-directional reflectance distribution function of surfaces, so as to match the shading throughout the work. Johnson and his colleagues built a computer graphics model of Vermeer's *Girl with a pearl earring* to test for lighting consistency inferred from other computer methods.[13] Stork and Nagy built a detailed model of Caravaggio's *The calling of St. Matthew* (Fig. 7), including the scattering properties of the rear wall, to infer the location and nature of the illumination source, so as to test for the artist's possible use of optical projections.[14,34] Stork and Furuichi built a model of Georges de la Tour's *Christ in the carpenter's studio* to determine if the light source in the tableau was indeed at the position of the depicted candle, or instead "outside the picture," as was claimed by artist David Hockney.[8,35] Although Stork and Furuichi's study of Diego Velàzquez's *Las meninas* centered on geometrical questions surrounding the reflected images of the king and queen reflected in the rear wall of the room, their model also permitted an analysis of the location and nature of the illumination sources in the tableau.[33]

We stress that although computer graphics models model physical processes of reflection, refraction, illumination falloff, and so on according to the laws of physics, our use of such models does not require us to assume the artist was "faithfully" or "photographically" representing the scene. Lighting analysis can be of fictive or imaginary scenes. Indeed, we can hypothesize that for a given artist, such as Rembrandt, the coherence or agreement might be higher for paintings from actual scene referent than for fictive scenes.

3. LIGHTING STYLE AND APPLICATIONS

There is no universally accepted taxonomy or even lexicon for describing lighting style in fine art, and indeed one of the goals of the current preliminary study is to encourage art scholars to develop such a vocabulary—one that is useful for art historical studies and specific enough that it can be computed. Perhaps such a taxonomy

Figure 7. Computer graphics model of Caravaggio's *The calling of St. Matthew*, used to test the location and nature of the illumination in the tableau. This rendering is based on a local, small, illuminant just outside the frame of the painting, and a diffusely reflecting rear wall.[14]

could be derived from the field of *lighting design* in computer graphics and still photography.[36] Informal art historical terms such as "harsh lighting," "soft lighting," "diffuse lighting," chiaroscuro, and so on may have more rigorous and agreed-upon descriptions. Flat, diffuse, or ambient light would correspond roughly to a lack of high-contrast cast shadows having small penumbrae, and to a large $l_{0,0}$ term in the expansion in Eq. 4 and the top figure in Fig. 5. Such a lighting style describes works such as Duccio di Buoninsegna's *Rucellai Madonna* and Lawrence Alma-Tadema's *A favorite custom*. Exaggerated light and dark, *chiaroscuro*, often arises with single point source illumination, as in Georges de la Tour's *Magdalen with the smoking flame*, Joseph Wright of Derby's *An experiment on a bird in the air pump* and many works by Caravaggio and Gerrit von Honthorst.

One of the most important descriptions of illumination is the overall direction, from the left (most popular in western), often to guide the eye and tell the story, as in Jacques-Lous David's *The oath of the Horatii*, or from the right, as in Hans Memling's *Portrait of a praying woman*. Likewise illumination from below, especially on a face as in Joseph Wright of Derby's *An experiment on a bird in the air pump* can convey a ghoulish tone to a work, particularly in night scenes

Another, rather straightforward, quantification of illumination is in the number and location of sources, such as single source, double source and so on. Modern portraitists sometimes refer to *butterfly lighting* (due to the resulting triangular shapes of the crossed shadows under a frontally posed nose) or occasionally *glamour lighting*. Such lighting could be computed and characterized from the locations of illuminants derived from cast shadows, highlights and the occluding-contour algorithm. "Rembrandt lighting" has been used to describe portrait light from 45°, as in his self portraits of 1629 and 1660.[37] Although art scholars can identify such lighting styles, perhaps algorithmic methods can refine these aspects of style.

Incommensurate and contradictory lighting is represented in the spatial variance among the inferred source locations for illuminants that should be commensurate. Quantitative measures based on the spatial spread of likely locations for an illuminant—a small such area implies a style of consistent or commensurate lighting while a large such area implies a style of inconsistent or incommensurate lighting—could be computed automatically as has been shown in studies of several realist works.[10, 24] We can hypothesize that this aspect of style may help to determine if an artist worked directly from the subject or instead from his or her imagination or preparatory works.

Some of the tasks that such rigorous lighting style analysis may assist include:

Artist identification Different artists may have different lighting styles, even for quite similar subjects.

Distinguishing works created from studio figures from works created from imagination It seems likely that works created from figural referents will have greater lighting consistency than do works created from the imagination, and thus that rigorous lighting analysis may help scholars in making such distinctions.

Distinguishing copies from originals As in the case just mentioned, there may be greater inconsistency in lighting in copies of artworks than in the original artworks, and thus rigorous image analysis might help distinguish copies from originals.

Diachronic studies of artistic development Just as traditional stylistic measures (brush strokes, perspectival coherence, and so on) may develop throughout an artist's career, so too we can expect that lighting style may develop throughout a career. As such, rigorous methods might help in dating works.

Testing for use of optical projections Lighting style—especially lighting location and relative intensity—can place strong constraints upon claims that an artist secretly traced optical projected images.

4. CONCLUSIONS

Clearly, the current effort is but a preliminary step toward computational tools for art scholars interested in lighting style in art. Much remains to be done in specifying the aspects of lighting that are most useful to the art community, the application to works in different media (oil on canvas, watercolor on paper, etc.), and then developing algorithms to reliably compute such measures, and testing them on works. Given that computer methods can be more reliable and accurate than human observers for detecting inconsistencies in digital photographs (as evidence of tampering, for instance), such computational methods may be more reliable and accurate than human observers for analogous measures in old master paintings.

Just as with some of the earliest applications of computer vision to problems in art history, the greatest use of lighting based stylometry may be for works and art historical questions yet to be identified by the art historical community. Nevertheless, we believe the preliminary directions identified here, and further dialog between art scholars and computer vision experts and image analysis, will help expand the study of art.[4,5,38]

ACKNOWLEDGMENTS

The author thanks Keith Christiansen of the Metropolitan Museum of Art for posing aspects of this research question and providing helpful suggestions, M. Kimo Johnson of MIT for assistance with software, and Gabor Nagy for leading the creation of the computer graphics model of Fig. 7. The author also thanks the staff of the Getty Research Center Library, Santa Monica, CA, where portions of this work were done.

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