

Lighting analysis of diffusely illuminated tableaux in realist paintings: An application to detecting “compositing” in the portraits of Garth Herrick

David G. Stork^a and Micah K. Johnson^b

^aRicoh Innovations, 2882 Sand Hill Road Suite 115, Menlo Park CA 94025 USA
and Department of Statistics, Stanford University, Stanford CA 94305 USA

^bDepartment of Brain and Cognitive Sciences, Massachusetts Institute of Technology,
Cambridge MA 02138 USA

ABSTRACT

The problem of estimating the direction of point-source illumination in digital photographs has been studied extensively, and the cast-shadow and occluding-contour algorithms have been used to detect tampering and compositing; differences between the lighting directions estimated from different objects indicate that at least one of them was composited into the image. Such methods have also been applied to the analysis of realist paintings to estimate the position of illuminants within a tableau and thereby test for artists’ use of optical aids. Recently, the occluding-contour algorithm has been enhanced to address the case of *diffuse* illumination, for instance from light passing through several windows, from multiple lamps, and so forth. Here, the pattern of lightness along the occluding contour of an object is expressed as a weighted sum of spherical harmonics. Significant differences between the coefficients extracted from different objects indicates that they were recorded under different illumination conditions, and thus that one or more was likely composited into the image. We apply this technique to the analysis of diffuse lighting in realist paintings, focussing on the portraits of the contemporary American realist Garth Herrick. Herrick often works with multiple photographs as referents, for instance a photograph of the portrait subject and a different photograph of the background. There is no guarantee that the two lighting conditions are the same, nor that Herrick can perceive or compensate for such lighting discrepancies when executing his painting. We tested for lighting consistency throughout two of his paintings: one based on a single photographic referent, and another “composited,” i.e., based on two photographic referents. Our algorithms found great illumination consistency in the first painting and significant inconsistencies in the second painting—inconsistencies difficult to discern by eye. As such, our methods reveal this artist’s working methods. Our algorithms have broad applicability to the study of studio practice throughout the history of art.

Keywords: painting analysis, image forensics, lighting analysis, spherical harmonics, occluding-contour algorithm, image tampering, image compositing, Garth Herrick, *Human on my faithless arm*, *Apotheoun*

1. INTRODUCTION

The task of estimating the direction of illumination in a realistic scene has been explored extensively in the computer vision and pattern recognition literature, and has been used in digital relighting of scenes and in forensic discovery of tampering and compositing.¹ The simplest model-independent method is based on cast shadows: one merely draws a line from a point on a cast shadow through its corresponding point on the occluder. Extended, this line will pass through the two-dimensional position of the illuminant. Multiple such lines, in general position, will intersect at the illuminant.² Another powerful model-independent method is the occluding-contour algorithm of Nillius and Eklundh.³ Here the direction perpendicular to the viewer’s line of sight and toward the illuminant is estimated from the pattern of brightness or gray scale along the occluding contour of an object. There are a number of model dependent methods as well—that is, ones that require knowledge or assumptions about the three-dimensional shape of the objects in the scene.⁴ In this paper we focus on a model-independent method

Send correspondence to David G. Stork, artanalyst@gmail.com.

because it is much easier to apply than model-dependent methods and, as we shall see, sufficiently powerful to answer questions in the history of art.

Recently, these methods have been applied to problems in the history of art, for instance testing objectively the consistency between different cues in Jan Vermeer’s *Girl with a pearl earring*,⁴ and testing for the use of optical projections by Georges de la Tour and Caravaggio.² Very recently, Stork⁵ as well as Kale and Stork⁶ pioneered *weakly* model-dependent methods for realist paintings. Specifically, they exploited the fact that floors and walls are flat and that they are vertical and horizontal, respectively. They derived maximum-likelihood equations for the illuminant position based on the measured luminance on such flat surfaces rendered in a painting. They applied their method to the floor in Georges de la Tour’s *Christ in the carpenter’s studio* and found that the light source was somewhat more likely in position of the candle than “in place of” either of the figures (Christ or St. Joseph). More specifically, they argued that based on their results they could not reject earlier conclusions that the light source was at the candle. Further, they applied their method to the rear wall in Caravaggio’s *The calling of St. Matthew* and found the illuminant was *local*, rather than distant solar. These two results rebutted David Hockney’s claim these paintings were executed by means of optical projections.⁷

The occluding-contour algorithm of Nillius and Eklund, mentioned above, applies to the case of a single, distant small or point-source illuminant. Recently, their technique has been generalized to the case of multiple or diffuse illumination sources.⁸ Here the pattern of brightness or graylevel along an object’s contour is expressed as a linear sum of spherical harmonics. This new method has been applied to the task of detecting tampering and compositing in digital photographs: significant differences between the coefficients in the sum of spherical harmonics for different objects implies that these objects were photographed under different lighting conditions and thus at least one object was composited into the image.

In this paper we apply this new diffuse illumination analysis technique to problems in the history and analysis of art, in particular detecting the analog of compositing in realist paintings. Suppose a realist artist executes one passage of a painting—a foreground figure, say—based on one photograph referent and a different part of the painting—the background, say—based on a different photograph referent. There is no guarantee that the lighting conditions in these two photographs are identical, nor that the artist visually can detect such illumination inconsistencies, nor that he can correct them as he executes his painting. The same situation might arise if the artist executes these different passages from life but each under different studio lighting conditions. In short, if an artist faithfully replicates the passages from different photographs into his painting, and the lighting is inconsistent between the photograph referents, our methods might be able to detect such “compositing.”

In Sect. 2 we describe the fundamental theory of occluding-contour-based lighting estimation for the general case of diffuse and multiple illuminants, following the recent work of Johnson and Farid.⁸ In Sect. 3 we describe the working methods of the American portraitist Garth Herrick. We analyze two of his paintings in Sect. 4, one executed with a single photographic referent, the other “composited”—that is, where the foreground figure was painted under one studio lighting condition and the background under a different studio lighting condition. As we shall see, our analysis of the first painting demonstrates Herrick’s ability to render the effects of illumination consistently under a single illumination condition. Our analysis of the second painting reveals statistically significant differences between the lighting on the foreground figure and the background, and this indicates that the artist used multiple referents, i.e., that he indeed “composited” his image. We mention some sources of error and uncertainty in our methods, and then conclude in Sect. 5 with some speculations and suggestions for the use of our methods in other works and problems in the history of art.

2. ESTIMATING LIGHT DISTRIBUTIONS FROM OBJECT CONTOURS

Our goal in this section is to describe a method for characterizing the illumination patterns in a scene based on brightness or grayscale measurements in an image. We seek a method that is model-independent (i.e., one that does not require knowledge or assumptions about the three-dimensional shape of objects in the scene) because such three-dimensional knowledge is difficult to obtain from the vast majority of realist paintings. We will use the lighting characterizations from different passages in a painting to test for inconsistencies in lighting and this, in turn, will reveal the possible use of different referents. The following theoretical derivation is a summary of the recent work Johnson and Farid,⁹ which has its roots in lighting characterization in shape-from-shading algorithms.¹⁰

Our measurements will be of the brightness or grayscale along the occluding contours of objects. We make the following assumptions in our derivation:

- Along each occluding contour used in our analysis, each object is Lambertian or diffusely reflecting—like skin or cloth, not specular like glass or metal.
- Each occluding contour used is of uniform reflectivity or albedo. (The method can be generalized if the albedo varies in a known way.)
- The illumination sources are reasonably far from each occluding contour so that the illumination coming from a given point on the source is parallel when the light strikes the objects.
- The camera capturing the scene or the artist recording the scene is reasonably far from the objects so that the projected image can be considered in orthographic perspective.
- Each object is convex so that there are no self-interreflections.
- Each object is reasonably far from other objects so that we can ignore the effects of interreflections from other objects.

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

$$E(\mathbf{n}) = \int_{\Omega} L(\mathbf{v})R(\mathbf{v}, \mathbf{n})d\Omega, \quad (1)$$

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. 1 as a sum over the orthogonal complete set of spherical harmonics,

$$L(\mathbf{v}) = \sum_{n=0}^{\infty} \sum_{m=-n}^n l_{n,m} Y_{n,m}(\mathbf{v}), \quad (2)$$

where $Y_{n,m}(\cdot)$ is the m^{th} spherical harmonic of order n , and $l_{n,m}$ is the coefficient describing the particular lighting environment. We assume the “camera function” i.e., the pixel- or point-wise mapping of luminance detected on the object to final image, is linear. (Non-linear extensions can be accommodated. [8, 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.

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.

Then the (truncated) brightness profile along an occluding contour becomes:

$$I(\mathbf{x}) = A + l_{1,-1} \frac{2\pi}{3} Y_{1,-1}(\mathbf{n}) + l_{1,1} \frac{2\pi}{3} Y_{1,1}(\mathbf{n}) + l_{2,-2} \frac{\pi}{4} Y_{2,-2}(\mathbf{n}) + l_{2,2} \frac{\pi}{4} Y_{2,2}(\mathbf{n}), \quad (3)$$

where the $l_{n,m}$ are the coefficients and

$$A = l_{0,0} \frac{\pi}{2\sqrt{\pi}} - l_{2,0} \frac{\pi}{16} \sqrt{\frac{5}{\pi}},$$

and the $Y_{i,j}(\cdot)$ depend only on the x and y components of the surface normal.

Equation 3 is linear in five lighting coefficients and can be expressed in matrix form:

$$\begin{pmatrix} 1 & \frac{2\pi}{3}Y_{1,-1}(\mathbf{n}(\mathbf{x}_1)) & \frac{2\pi}{3}Y_{1,1}(\mathbf{n}(\mathbf{x}_1)) & \frac{\pi}{4}Y_{2,-2}(\mathbf{n}(\mathbf{x}_1)) & \frac{\pi}{4}Y_{2,2}(\mathbf{n}(\mathbf{x}_1)) \\ 1 & \frac{2\pi}{3}Y_{1,-1}(\mathbf{n}(\mathbf{x}_2)) & \frac{2\pi}{3}Y_{1,1}(\mathbf{n}(\mathbf{x}_2)) & \frac{\pi}{4}Y_{2,-2}(\mathbf{n}(\mathbf{x}_2)) & \frac{\pi}{4}Y_{2,2}(\mathbf{n}(\mathbf{x}_2)) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \frac{2\pi}{3}Y_{1,-1}(\mathbf{n}(\mathbf{x}_p)) & \frac{2\pi}{3}Y_{1,1}(\mathbf{n}(\mathbf{x}_p)) & \frac{\pi}{4}Y_{2,-2}(\mathbf{n}(\mathbf{x}_p)) & \frac{\pi}{4}Y_{2,2}(\mathbf{n}(\mathbf{x}_p)) \end{pmatrix} \begin{pmatrix} A \\ l_{1,-1} \\ l_{1,1} \\ l_{2,-2} \\ l_{2,2} \end{pmatrix} = \begin{pmatrix} I(\mathbf{x}_1) \\ I(\mathbf{x}_2) \\ I(\mathbf{x}_3) \\ \vdots \\ I(\mathbf{x}_p) \end{pmatrix} \quad (4)$$

or $\mathbf{M}\mathbf{w} = \mathbf{b}.$

Equation 4 yields the least-squares solution for the coefficients:

$$\mathbf{w} = (\mathbf{M}^t\mathbf{M})^{-1} \mathbf{M}^t\mathbf{b}. \quad (5)$$

If the range of orientations of a given occluding contour is small, or the visual evidence is noisy, though, computing the solution through Eq. 5 may prove unstable or unreliable; thus we may introduce a regularization term to avoid such instabilities. After a straightforward derivation following the above, we find a more robust solution,

$$\mathbf{w} = (\mathbf{M}^t\mathbf{M} + \lambda\mathbf{C}^t\mathbf{C})^{-1} \mathbf{M}^t\mathbf{b}, \quad (6)$$

where λ is a scalar that controls the smoothness of the solution. We can find the best single light direction and ambient term by first removing the fourth and fifth columns of \mathbf{M} and solving for the coefficients in Eq. 4. Then the principal light direction is given by the terms $l_{1,-1}$ and $l_{1,1}$ in this reduced-matrix solution, specifically

$$\theta = \tan^{-1}(l_{1,-1}/l_{1,1}). \quad (7)$$

2.1 Quantifying illumination matches

Suppose we estimate the five-dimensional illumination vectors for two objects in a scene, \mathbf{w}_1 and \mathbf{w}_2 . How do we know if these differ significantly, that is, more than can be expected by chance and thus that the illumination conditions differed for the two objects? We quantify the match between such estimated vectors by a normalized correlation,

$$\text{corr}(\mathbf{w}_1, \mathbf{w}_2) = \frac{\mathbf{w}_1^t \mathbf{Q} \mathbf{w}_2}{\sqrt{\mathbf{w}_1^t \mathbf{Q} \mathbf{w}_1} \sqrt{\mathbf{w}_2^t \mathbf{Q} \mathbf{w}_2}}, \quad (8)$$

where $\mathbf{Q} = \text{diag}(0 \ \pi/6 \ \pi/6 \ 5\pi/4 \ 5\pi/4)$ is required for technical reasons of normalization. A natural measure of error is then represented by a “distance,”

$$D(\mathbf{w}_1, \mathbf{w}_2) = \frac{1}{2}(1 - \text{corr}(\mathbf{w}_1, \mathbf{w}_2)), \quad (9)$$

which is normalized such that $0 \leq D(\mathbf{w}_1, \mathbf{w}_2) \leq 1$. A small D implies the illumination conditions are likely very similar; a large D implies the illumination conditions are likely very different.



Figure 1. (left) Photographic referent used by Mr. Herrick for the fireplace in the background of a portrait of Philadelphia Mayor Rendell, where the artist is standing in for the subject. (right) Garth Herrick, *Mayor Edward G. Rendell* (2002), 127 × 96.5 cm, oil on linen (Collection of the City of Philadelphia, City Hall). Mr. Herrick executed this painting in his studio, using two photograph as referents: the one show on the left (for the background) and a different photograph, of the subject. As such, the final painting can be considered the analog of a “composited” digital photograph.

3. THE PORTRAIT TECHNIQUES OF GARTH HERRICK

Garth Herrick (b. 1958) is a professional realist painter working near Philadelphia PA, noted for his technical mastery and the formal dignity befitting many of his commissioned subjects, such as political figures (*Mayor Edward G. Rendell*, 2002, *Lieutenant Governor Mark S. Singel*, 2003), judges (*The Honorable William Marutani*, 2003, *The Honorable James T. Giles, Chief Judge*, 2006), social leaders (*Daniel DiLella, President*, 2006) and scholars (*Dr. Earl Ball, Head*, 2005). Herrick frequently works from photograph referents, and sometimes adjusts overall lightness and color balance in Adobe *Photoshop* on a computer before working in oil on canvas.¹¹ He does not project an image onto his canvas or trace such an image but alters the image slightly, while painting, for expressive and compositional ends. He often works from multiple photographic referents, for practical reasons. Thus he may use a photograph of a background and a different photograph of a figure for the foreground, and paint using both these referents. Figure 1 shows his background photograph referent, and his final portrait, *Mayor Edward G. Rendell*.

In other cases Herrick works from life, in the studio. Here too, however, he may employ multiple studio configurations and lightings for different portions of the image. Thus he may paint the background in one studio condition, and the foreground in a very different studio condition, as in his *Human on my faithless arm*, shown in Fig. 3 below.

4. LIGHTING ANALYSIS OF HERRICK’S PAINTINGS

We analyzed the lighting consistency within each of two paintings by Garth Herrick. First, we converted each painting to grayscale and then applied the algorithm described in Sect. 2. Figure 2 shows *Apotheoun*, a work executed from a single photograph referent. We estimated five lighting environment coefficients for the boy, \mathbf{w}_1 , and for his mother, \mathbf{w}_2 , as described above. Table 1 shows our results. Recall that θ is the predominant lighting direction, as defined in Eq. 7, above. The distance between the two five-dimensional vectors, Eq. 9 was 0.06—quite small on the scale 0–1. This small distance demonstrates that Herrick could accurately render lighting information under a single lighting condition.

Figure 3 shows the second painting we analyzed, *Human on my faithless arm*. Herrick painted this work under two lighting conditions: the architectural scroll from life, in a studio, and his nude self-portrait under

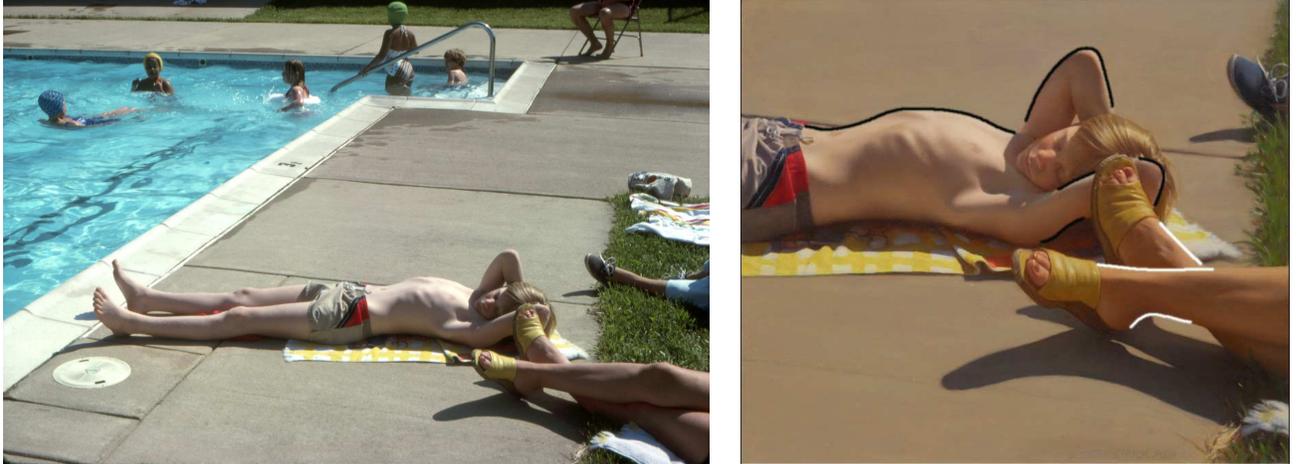


Figure 2. (left) Photograph, taken in 1981, later used as a referent for *Apotheoun*. (right) Garth Herrick, *Apotheoun* (2004), 77.5 × 90.2 cm, oil on linen (collection of the artist). We used the contours on the boy (marked in black) and the contours on the mother’s legs (marked in white) to estimate the coefficients in a spherical harmonic representation of the lighting distributions. The coefficients were statistically indistinguishable, showing there was a single lighting condition as well as that the artist could render such illumination information consistently (cf. Table 1).

contours	A	$l_{1,-1}$	$l_{1,1}$	$l_{2,-2}$	$l_{2,2}$	θ	ambient component
boy	0.4246	-0.2275	0.1198	-0.1114	0.0232	58.4°	0.4055
mother	0.3840	-0.1554	0.0152	-0.1734	0.0961	61.2°	0.3554

Table 1. The spherical harmonic coefficients estimated from two sets of occluding contours in *Apotheoun* (cf., Fig. 2). Note especially the excellent agreement between these coefficients, and between the principle angles, θ .

different lighting conditions, in a mirror. Table 2 shows our results. Notice especially that the distance between the two five-dimensional vectors is 0.3734, again, on a scale 0–1. This distance is much larger than for the case of *Apotheoun*, and exposes the fact that Herrick indeed worked under two lighting conditions when executing this painting.

contours	A	$l_{1,-1}$	$l_{1,1}$	$l_{2,-2}$	$l_{2,2}$	θ	ambient component
scroll	0.1480	-0.0328	0.4342	-0.4207	-0.3240	53.0°	0.3163
leg & arm	0.5561	-0.2196	-0.0071	-0.1569	-0.2867	83.4°	0.6153

Table 2. The spherical harmonic components estimated from two sets of occluding contours in *Human on my faithless arm* (cf., Fig. 3). Note especially the large difference between these coefficients, and between the principle angles, θ .

5. CONCLUSIONS

We have demonstrated that algorithms for estimating illuminant distributions in general, diffuse conditions, can reveal aspects of the working method of at least one talented realist painter. Such “compositing” is not immediately evident through visual inspection of the painting itself. We believe our methods will be similarly revealing about other artists as well, though of course this is future work.

There needs to be more work on the fundamental algorithms themselves. For instance, we need principled methods for setting thresholds to indicate when D in Eq. 9 is “too large” and thus the illumination conditions differ greater than can be expected by chance. Surely such a threshold could be estimated statistically from a set of images created under known conditions,¹² but a more principled approach would be based directly on statistical assumptions of the illumination and associated uncertainties. Perhaps, too, there are better functional measures of “distance,” that is, ones tailored to those statistical assumptions about the lighting.

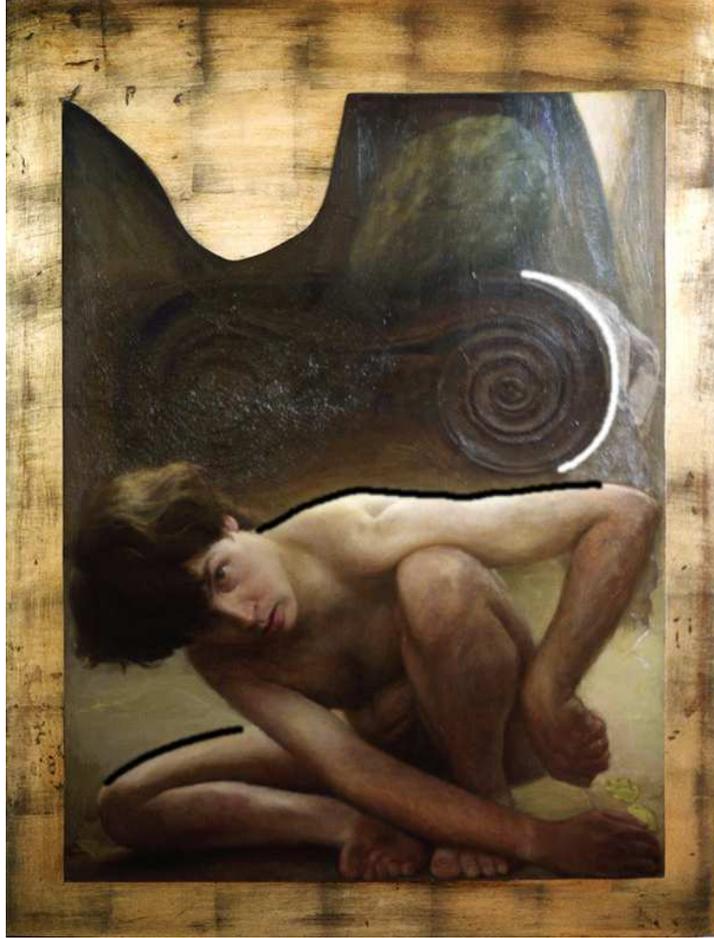


Figure 3. Garth Herrick, *Human on my faithless arm* (1995), 101.6 × 76.2 cm, oil on shaped wooden panel (private collection). We used the contours on the subject (marked in black) and the contours on the architectural scrollwork (marked in white) to estimate the coefficients in a spherical harmonic representations of the lighting distributions. The sets of coefficients differed significantly, indicating that the artist rendered these parts of the painting under different illumination conditions (cf. Table 2).

How might applying these and related illumination estimation methods^{1,2,13,14} to other artworks help humanist art scholars? One application would be *attribution*, that is, determining which “hands” were responsible for different portions, such as figures, within a given painting. For instance, it is well known that Verrocchio executed the figure of Christ, and Leonardo the two angels in *The baptism of Christ* (1472–1475). This is clear from the differences in brush strokes, color, and general shading. Perhaps our techniques would reveal differences in effective lighting as well.

Finally, we believe scholars and researchers in computer vision and pattern recognition should work closely with art scholars to integrate these algorithms with the growing body of computer methods of value in the study of art and to address questions of interest to the art community.¹⁵

ACKNOWLEDGMENTS

Micah K. Johnson was supported by an NSF University-Industry Cooperative Research Grant. We would like to thank artist Käthe Grinstead for bringing to our attention the works of Garth Herrick, and especially to thank Mr. Herrick for explaining his studio technique and granting permission to reproduce his paintings and photographs.

REFERENCES

1. M. K. Johnson and H. Farid, “Exposing digital forgeries by detecting inconsistencies in lighting,” in *ACM Multimedia and Security Workshop*, pp. 1–9, ACM, New York, NY, 2005.
2. D. G. Stork, “Did Georges de la Tour use optical projections while painting *Christ in the carpenter’s studio?*,” in *SPIE Electronic Imaging: Image and video communications and processing*, A. Said and J. G. Apostolopoulos, eds., **5685**, pp. 214–219, SPIE, (Bellingham, WA), 2005.
3. P. Nillius and Jan-Olof Eklundh, “Automatic estimation of the projected light source direction,” in *IEEE Conference on Computer Vision and Pattern Recognition (CVPR01)*, **1**, pp. 1076–1083, 2001.
4. M. K. Johnson, D. G. Stork, S. Biswas, and Y. Furuichi, “Inferring illumination direction estimated from disparate sources in paintings: An investigation into Jan Vermeer’s *Girl with a pearl earring*,” in *Computer image analysis in the study of art*, D. G. Stork and J. Coddington, eds., **6810**, pp. 68100I–1–12, SPIE/IS&T, Bellingham, WA, 2008.
5. D. G. Stork, “Locating illumination sources from lighting on planar surfaces in paintings: An application to Georges de la Tour and Caravaggio,” in *Optical Society of American Annual Meeting*, p. (abstract), OSA, (Rochester, NY), 2008.
6. D. Kale and D. G. Stork, “Estimating the position of illuminants in paintings under weak model assumptions: An application to the works of two Baroque masters,” in *Electronic Imaging*, p. (in press), SPIE/IS&T, Bellingham, WA, 2009.
7. D. Hockney, *Secret knowledge: Rediscovering the lost techniques of the old masters*, Viking Studio, New York, NY, 2001.
8. M. K. Johnson and H. Farid, “Exposing digital forgeries through specular highlights on the eye,” in *Proceedings of the 9th International Workshop on Information Hiding*, T. Furon, ed., *Lecture Notes in Computer Science* **4567**, pp. 311–325, Springer, (Saint Malo, France), 2007.
9. M. K. Johnson and H. Farid, “Exposing digital forgeries in complex lighting environments,” *IEEE Transactions on Information Forensics and Security* **2**(3), pp. 450–461, 2007.
10. R. Ramamoorthi and P. Hanrahan, “An efficient representation for irradiance environment maps,” *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques*, pp. 497–500, 2001.
11. M. S. Doherty, “Unlocking a subject’s personality,” *American Artist* **72**(788), pp. 36–43, 2008.
12. R. O. Duda, P. E. Hart, and D. G. Stork, *Pattern classification*, John Wiley and Sons, New York, NY, Second ed., 2001.
13. D. G. Stork and M. K. Johnson, “Estimating the location of illuminants in realist master paintings: Computer image analysis addresses a debate in art history of the Baroque,” in *Proceedings of the 18th International Conference on Pattern Recognition*, **I**, pp. 255–258, IEEE Press, (Hong Kong), 2006.
14. D. G. Stork and M. K. Johnson, “Computer vision, image analysis and master art, Part II,” *IEEE Multimedia* **14**(3), pp. 12–17, 2006.
15. D. G. Stork and J. Coddington, eds., *Computer image analysis in the study of art*, vol. 6810, SPIE/IS&T, Bellingham, WA, 2008.