Inferring Caravaggio’s studio lighting and praxis in
The calling of St. Matthew by computer graphics modeling

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ABSTRACT
We explored the working methods of the Italian Baroque master Caravaggio through computer graphics reconstruction of his studio, with special focus on his use of lighting and illumination in The calling of St. Matthew. Although he surely took artistic liberties while constructing this and other works and did not strive to provide a “photographic” rendering of the tableau before him, there are nevertheless numerous visual clues to the likely studio conditions and working methods within the painting: the falloff of brightness along the rear wall, the relative brightness of the faces of figures, and the variation in sharpness of cast shadows (i.e., umbrae and penumbrae). We explored two studio lighting hypotheses: that the primary illumination was local (and hence artificial) and that it was distant solar. We find that the visual evidence can be consistent with local (artificial) illumination if Caravaggio painted his figures separately, adjusting the brightness on each to compensate for the falloff in illumination. Alternatively, the evidence is consistent with solar illumination only if the rear wall had particular reflectance properties, as described by a bi-directional reflectance distribution function, BRDF. (Ours is the first research applying computer graphics to the understanding of artists’ praxis that models subtle reflectance properties of surfaces through BRDFs, a technique that may find use in studies of other artists.) A somewhat puzzling visual feature—unnoted in the scholarly literature—is the upward-slanting cast shadow in the upper-right corner of the painting. We found this shadow is naturally consistent with a local illuminant passing through a small window perpendicular to the viewer’s line of sight, but could also be consistent with solar illumination if the shadow was due to a slanted, overhanging section of a roof outside the artist’s studio. Our results place likely conditions upon any hypotheses concerning Caravaggio’s working methods and point to new sources of evidence that could be confirmed or disconfirmed by future art historical research.

Keywords: Caravaggio, The calling of St. Matthew, computer graphics, tableau virtuel, bi-directional reflectance distribution function, BRDF, Baroque art

1. INTRODUCTION
Recently computer graphics has proved a promising tool in art historical research, particularly in studies of lighting and perspective. Stork and Furuichi built a computer graphics model of Georges de la Tour’s Christ in the carpenter’s studio and adjusted the position of the virtual illuminant and thereby found that the visual evidence was far more consistent with the illuminant in place of the candle than in place of the other figures. This empirical result and supporting art historical evidence led to a rejection of claims this painting was executed under optical projections.\textsuperscript{1} Stork used computer graphics to test claims that the chandelier in Jan van Eyck’s Arnolfini portrait “is in perfect perspective” and hence likely executed by tracing a projected image.\textsuperscript{2,3} These computer-graphics based results, and those of rigorous computer vision analysis, showed the chandelier differed significantly from proper perspective, far too much to be consistent with the optical projection claim.\textsuperscript{4} Even the small regions of the Arnolfini chandelier in fair perspective were no more accurate than comparable passages in paintings of chandeliers executed without drawing aids.\textsuperscript{5} Johnson and his colleagues used computer graphics as one of six methods to infer the direction of illumination in Jan Vermeer’s Girl with a pearl earring. These scholars found excellent agreement among the semi-independent methods—to less than 4°—a testament to both Vermeer’s mastery in rendering the effects of light and to the power of these computer methods in aiding the interpretation of realist paintings.\textsuperscript{6}

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Paintings by the Italian Baroque master Caravaggio (1571–1610) generally portray religious scenes with figures in a shallow stage-like space, lit by dramatic, raking light of tenebrism and in pronounced chiaroscuro. His works greatly influenced Georges de la Tour, Gerrit von Honthorst and others, who became known as Caravaggisti, and his many breaks from tradition painting led Andre Berne-Joffroy to proclaim: “What begins in the work of Caravaggio is, quite simply, modern painting.” His contemporary commentators criticized the artist for working directly from figures without (by their reckoning) sufficient idealization of the religious subjects he portrayed; indeed, we have no surviving drawings by this artist’s hand. Such a pronounced departure from the prevailing painterly conventions immediately raises technical questions about Caravaggio’s studio and working methods. In the absence of contemporary eye-witness records describing his working methods, modern scholars have long speculated on his working practice, such as the nature of the light (direct solar versus local lamps), specific studio layout, praxis (e.g., whether figures were painted one at a time or as a group), and even whether he secretly traced optical projections.

We attempted to infer Caravaggio’s lighting conditions and studio working methods by building a realistic computer graphics model (or tableau virtuel) of The calling of St. Matthew and adjusting the location and intensity of the primary light source, the reflectance properties of surfaces such as the rear wall, and the geometry of architectural elements outside the frame, all to match as closely as possible the relevant visual evidence in the painting. We hypothesized a number of plausible studio procedures consistent with our models and the image evidence—procedures that must now be judged by art scholars deeply versed in Italian Baroque methods in general and Caravaggio’s possible methods in particular.

In related work, Kemp described the construction of a full, life-sized physical model to infer Caravaggio’s working methods. While a physical model might reveal some subtle binocular and reflective effects a bit better than does computer graphics, such a physical model does not afford the ability to change properties such as the reflectances of surfaces or major architectural features which, as we shall see, may be important for understanding The calling of St. Matthew. Likewise, such a physical model becomes prohibitively expensive when the tableau includes many human figures.

We begin in Sect. 2 describing Caravaggio, his work we shall consider, and the questions we address. Much of our computer modeling will rely on matching visual properties in the painting, and thus in Sect. 3 we briefly review the relevant physics of illumination and lighting. We describe our modeling methodology in Sect. 4 and turn to our primary results—specifically a comparison of local illumination and solar illumination models—in
Sect. 5. We conclude in Sect. 6 with lessons learned, directions for further analysis of Caravaggio’s works, as well as some words of guidance for the application of computer graphics elsewhere in the study of fine art.

2. CARAVAGGIO, STUDIO PRAXIS, AND THE CALLING OF ST. MATTHEW

Michelangelo Merisi da Caravaggio led a tumultuous life in which he fought in brawls, killed a man, fled the law, and more. He broke from the prevailing and somewhat contrived or artificial style of Mannerism, in which figures were often distorted or elongated and placed in crowded tableaus, by introducing a style based on careful observation, realism, dramatic illumination and chiaroscuro. His early commissions in Rome, including The calling, established his reputation and in the early 17th century he was called the most famous painter in Rome.

The painting we consider, The calling of St. Matthew, depicts the Biblical story of Christ calling the Jewish tax collector (or publican) named Matthew or Levi, beckoning him to leave his worldly endeavors and instead to “follow me” (Matthew 9:9). The painting is typical of Caravaggio’s oeuvre: a poignant religious episode in a shallow space, dramatic lighting, animated by powerful human gestures (Fig. 1). We confine our attention to the following technical questions: What was the primary source of illumination in the tableau? Was it local (artificial) light such as oil lamps, or instead the sun? Did the artist paint the figures together as a single group or instead in several small groups?

3. THE PHYSICS OF ILLUMINATION AND OBJECT APPEARANCE

There are three aspects of the physics of light and its interaction with objects that are most relevant to our analysis of The calling: 1) shadows, including cast-shadows, form shadows, umbrae and penumbrae, 2) the appearance of illuminated surfaces, and 3) the overall intensity of projected images. The first two are incorporated into the physical models of all computer graphics rendering software, including the one we use, Equinox3D. There are of course many other closely related topics relevant to the analysis of other paintings, such as color or color temperature, spatial depth, and subtleties of brush strokes, but these need not concern us here.

3.1 Cast shadows

The physics of cast shadows is well understood, though we remind the reader that there is a fundamental difference between a cast shadow, in which an occluder or blocker casts a shadow onto a separate object, and a form shadow or attached shadow, in which the shadow is on the object itself. Here we will focus on cast shadows, though of course our computer graphics modeling also renders form shadows. Cast shadows may consist of an umbra (full shadow) and a penumbrae (partial shadow), and the relationship between these two provide information about the size or spatial extent of the light source.

Figure 2. A small-area light source, i.e., one that subtends a small visual angle, leads to relatively sharp cast shadows of the vertical block (left figure), while a large-area light source leads to larger region of partial shadow—penumbrae (right figure). If the shadow receiver surface and the occluder are in contact, the cast shadows are sharp near the base of the occluder (“contact shadow”), even in the large-area light source case.

Figure 2 illustrates some of the basic physics of cast-shadows we shall exploit: the effect of source size on the appearance of penumbrae or partial shadows. At the left is a small source, which produces a crisp cast shadow of the vertical block—almost entirely an umbra or full shadow. At the right is a large source, and here the umbra
is smaller and the region of penumbra is large. Note, though, that even for this large source, the edge of the
cast shadow is sharp near the base of the block, and becomes softer and more diffuse further back. For a given
three-dimensional geometry, the size of the penumbra indicates the effective size of the illumination source.

One of the light sources we consider for *The calling* is the sun. While the sun’s disk subtends 0.5° visual
angle, there is scattering in the atmosphere which increases its effective size. The closer the sun is to the horizon,
the thicker the atmosphere through which its light passes, the greater the proportion of light that is scattered,
and hence the larger the sun’s effective source diameter. We shall test whether the shadows and penumbrae on
the wall in *The calling* are consistent with such solar illumination.12

### 3.2 Surface appearance models

The appearance of an illuminated surface depends fundamentally upon the physical properties of that surface, and
decades of computer graphics research has led to a number of computational models to describe and render such
surfaces. These models are generally expressed as bi-directional reflectance distribution functions, or BRDFs,
which describe the relative intensity of a light beam striking the surface along direction $v_i$ that is scattered into
viewing direction $v_o$. The bi-directional reflectance distribution function is defined by

$$f_r(v_i, v_o) = \frac{dL_r(v_o)}{dE_i(v_i)} = \frac{dL_r(v_o)}{L_i(v_i) \cos \theta_i \, dv_i}.$$  

(1)

where $\theta_i$ is the angle of incidence (the angle between the normal $n$ and the vector $v_i$), $E(\cdot)$ is incident irradiance and $L(\cdot)$ is the reflected radiance.13

![Specular Lambertian Cook-Torrence](image)

Figure 3. The relative intensity of light reflecting at different angles from a surface depends upon the physical properties
of that surface. Here a horizontal surface has unit normal vector $n$. A ray incident along $v_i$ strikes the surface at angle $\theta_i$.
If the surface is purely specular, such as a mirror, then the reflected light is also a beam, here at $\theta_r = \theta_i$ as determined by
the Law of Reflection (left figure). If the surface is instead Lambertian, the reflected light is independent of the direction
of the viewing direction (middle figure). A more powerful and general model is the Cook-Torrance model, based on a
surface with microfacets with a specific angular distribution (right figure). Some surfaces can be described as weighted
mixtures of such reflectance models (cf., Fig. 4).

Perhaps the simplest BRDF is that for a perfect reflector or mirror, where $f_r(v_i, v_o) \propto \delta(v_i - v_o)$, $\delta(\cdot)$ is the
multi-dimensional Dirac delta function, and $v_r$ describes the direction of a beam obeying the (specular) Law of
Reflection. The other extreme for a BRDF is that describing a matte surface or perfect diffuse reflector, described
by Lambert’s Cosine Law, leading to an $f_r(v_i, v_o)$ independent of the viewing direction $v_o$. The Lambertian
model is a good approximation for surfaces such as most cloth and even dry skin; any given Lambertian surface
looks equally bright when viewed from every direction. This model has been used by Kale and Stork in the
analysis of lighting in art, specifically to model the appearance of the floor in Georges de la Tour’s *Christ in the
carpenter’s studio* and the rear wall in Caravaggio’s *The calling of St. Matthew*.14 We are aware that fading of
pigments in the painting would complicate our analyses somewhat, though such fading would preserve the fact that there is a luminance gradient along the wall—the key empirical evidence we explore.

The reflectance of some objects, such as rough metal doorknobs, can be modeled as a weighted sum of specular and diffuse reflections (Fig. 3). The most general form of a BRDF includes the color or wavelength dependence of light—crucial for modeling luster as in pearls and some minerals—but we can ignore this complication in the current study. Figure 4 shows spheres having different reflectivity properties, the Lambertian model or perfect diffuse reflector at the left, giving a matte surfaces such as soft cloth, and the nearly specular reflector at the right, giving a shiny or mirror-like surface.

![Figure 4. The reflectance of the matte sphere at the left is due primarily to diffuse or Lambertian reflectance while the reflectance of the figure at the right is primarily specular or mirror-like reflectance. The BRDFs of the intermediate spheres are weighted sums of diffuse and specular reflections. A very wide range of surface appearances can be modelled through complicated BRDFs.](image)

### 3.3 Brightness of projected images

We mention in passing an aspect of the physics of optical projections. The brightness (or more properly luminance) of an image projected by a simple optical element such as a concave mirror or converging lens, $I_p$, is related to the brightness of the source object in the world, $I_w$, by

$$\frac{I_p}{I_w} = \rho \frac{A}{f^2} \cos^4 \alpha,$$

where $\alpha$ ($0 \leq \alpha \leq \pi/2$) is the angle with respect to the optical axis, $\rho$ ($0 \leq \rho \leq 1$) is the reflectivity of the concave mirror or transmissivity of the concave lens, $A$ is the facial area and $f$ the focal length of the mirror or lens. Typical brightness reductions for elements from the Renaissance are a factor of 1000, the equivalent of stacking three commercial sunglasses atop one another.$^{15}$ The reduction for elements from Caravaggio’s time (17th-century) may be just a bit smaller. The case of catadioptric systems, which comprise both lens and mirror elements, is yet more complicated.$^{16}$ For an image to be useful to an artist around Caravaggio’s time, before high-power theatrical stage lighting, the illumination must be sunlight. As such, our results, below, may shed light upon claims this 17th-century artist employed optical projections$^8$—a topic we defer to our ongoing research. We can state here, though, that if it can be shown that Caravaggio worked in dark basements by artificial light, as has been claimed,$^{17}$ then these illumination requirements alone would rule out any claim this artist directly traced projected images.

### 4. METHODOLOGY

As mentioned in Sect. 2, our central art historical questions concern the nature of the illumination in Caravaggio’s studio, specifically whether the illumination is local (and hence artificial) or distant and solar. Our approach is to create two models, one for each case, and adjust the model parameters to produce an image as consistent as possible with that in the painting. If we can create no such consistent model, it makes the corresponding lighting condition unlikely. The features of a matching model can then be judged for plausibility by the wider community of art scholars. Moreover, any significant difference between our “best” model and the painting may reveal how and where the artist took expressive liberties and deviated from a mere “photographic” recording of the direct
studio scene before him—that is, we did not model the artistic liberties taken by the artist. Our models, thus, may reveal the artistic liberties and decisions taken by the artist as he constructs the image. For example, Joseph Anton Koch, *Noah's Thanks offering* (c. 1803) depicts a rainbow violating numerous laws of physics. Modeling Koch’s image with physics based computer graphics software in no way assumes this artist is attempting to be “photographic” but rather reveals his artistic deviations from objective reality. Koch surely added the rainbow to this work not from observation but instead from memory and to convey metaphorical significance, here as a signal to Noah from God.

We created our three-dimensional computer graphics models using *Equinox3D*, a freeware system developed by the present first author. Each model is meant to capture the paintings as we see it, and only indirectly the studio itself. The creation of a three-dimensional model from a two-dimensional image is formally ill-posed: there is an infinite number of three-dimensional scenes that project to the same two-dimensional image. As such, we must impose constraints when creating our model. Some are a near certainty, for instance that the surfaces of walls, floor, table, and so on are planar; others are extremely likely, for instance that the figures have nearly normal body proportions, symmetric faces, and so on. Occlusion is a powerful constraint upon our model and reveals which objects are closer than others, as are the laws of gravity and physics of contact, for instance that bodies are supported by, and hence touch, the floor.

There are certain properties of the painting that we can confidently ignore, such as color and details of facial expressions, as these bear no relation to the problems at hand. Furthermore, while there will necessarily be uncertainties in our model creation, we need merely ensure that these assumptions do not bias our answers; in the terminology of statistical estimation, we seek an unbiased estimation of the properties revealed by the painting even though there will inevitably be variance. We later adjust parameters and properties its reflectance properties under the different lighting conditions. Moreover, we followed the methodological recommendations advocated by Stork and Furuichi for the use of computer graphics in art, in which two (or more) models are created so as to better isolate their key differences and how these shed light on the art historical questions at hand.

5. RESULTS AND INTERPRETATIONS

Figure 1, above, shows Caravaggio’s painting and one of our basic computer graphics rendering, which we adjust and study. We begin by exploring our local illumination model and then turn to our solar illumination model.

5.1 Local illumination model

Figure 5, above, shows our local source model, including a simple rectangular window outside the frame of the painting; the rear wall is modeled as a diffusely reflecting or Lambertian model with uniform BRDF. This model can well describe the falloff in lumiance on the wall away from the source (that is, reading right to left). Note, however, that the faces of the figures at the left are far darker than the images in the painting, owing to the fairly large ratio of distances from the source and the $1/r^2$ falloff in intensity. Even allowing for the compressively nonlinear response of the human visual system, the figures at the left in the painting would appear significantly darker than those at the right. For Caravaggio to create the painting as we find it under the local lighting conditions—in which the figures are nearly equally bright—he would have had to adjust “by eye” the figure brightnesses. This would have been fairly simple had he executed the figures individually or in small groups, as has been suggested.

5.2 Solar illumination model

Figure 6, below, shows our model with distant, solar illumination. As one can deduce from first principles and as can be confirmed through our modelling, a pure Lambertian reflectance model for the rear wall is incompatible with the visual evidence in the painting; a Lambertian wall under solar illumination would appear uniformly bright. We adjusted the BRDF and found that the best fit to the visual evidence was a Blinn-Torrance microfacet model with eccentricity 0.68. We need not explore the details of this microfacet model here except to say that it is plausible as a model for a somewhat rough wall, for instance one made of plaster or even some types of wood.
In the solar illumination model, the upward-slanting cast shadow at the upper right in the painting is incompatible with the physical model of the perpendicular window of Fig. 5; illumination from the sun cannot cast such an upward-slanting shadow through such a window. This upward-directed shadow is analogous to that in the upper left of Caravaggio’s *The death of the Virgin* (c. 1601–3), which, like the light striking the ceiling in that painting, is incompatible with solar illumination. The penumbras along that cast shadow are generally compatible with the solar configuration and geometry of the architecture. Perhaps Caravaggio added this shadow in *The calling* for compositional or artistic reasons, though it seems more likely that this astute observer and “stage director” would have created it in the studio, and would easily allow him to accurately render the penumbras.

But how to explain this peculiar upward-slanting shadow, one that has not been noted in the art historical literature? The most plausible configuration we found is shown in the right in Fig 6 and more fully in Fig. 7, where the cast shadow is due to a slanted overhanging cornice of a roof outside Caravaggio’s studio. This occluder produces the narrow but broadening penumbra we find in the cast shadow on the rear wall. We leave the question of the plausibility of this cornice explanation to historians of the architecture of 17th-century Rome and to art historians versed in Caravaggio’s life and studios. At the very least, the solar illumination model is incompatible with a northward-facing window, which would never admit direct sunlight (see Sect. 6).

We remind the reader that sun moves half degree visual angle every two minutes, and the change in angle of the primary cast shadow would have been significant over the time it would take any artist to render the portion—likely days or weeks. If Caravaggio painted this shadow from careful observation, he would surely have had to merely sketch the shadow (perhaps in chalk) and then later fill in the areas with paint.
5.3 Sight lines in the tableau

We mention briefly that our models can be used for other tasks, for instance revealing sight lines and views from within the tableau itself. For example, it may be unclear from the painting itself which figures can and cannot see each other, where a given figure is pointing, as for instance the identity of the figure in *The calling* towards which Christ is pointing, which figures can and cannot see Christ, and so on. Likewise, if there is a significant discrepancy between sight lines and viewing directions among figures within a tableau, such evidence might indicate the artist executed the figures *individually* and thus without proper “targets” for sight lines. We leave such sight line analysis to ongoing work, but illustrate such use of computer graphics models in Fig. 8.
6. CONCLUSIONS

We explored Caravaggio’s likely studio and illumination conditions in The calling of St. Matthew through computer graphics rendering. We found that a falloff in luminance on the rear wall could be consistent with distant solar illumination if the wall had a particular bi-directional reflectance distribution function BRDF. The only plausible physical model we found consistent with the upward-slanting shadow of an overhanging roof, outside the studio. Such a model could be consistent, too, with the penumbrae of that shadow. The upward-angled shadow at the upper right corner of the painting is consistent with light from a local source passing through a window in a wall at the right.

While our results cannot be considered definitive, they refine and constrain speculations about Caravaggio’s working methods and studio, and provide directions to art historians seeking more information about his methods and studio, such as architecture outside the studio. We believe computer graphics methods, when tightly linked to known contextual, historic and art historical knowledge, may continue to shed light on a range of problems in the history of art. Such models, too, may facilitate dialog between art scholars and computer scientists.23,24

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