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Toward the Accuracy of Lighting Simulations in Physically Based Computer Graphics Software

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This project evolved from an interest in validating the accuracy of lighting visualization software tools. It is reasonable to ask if visualization software is numerically accurate. In fact, it is necessary to answer this question if software computed luminance values will be used for lighting design, analysis, or research.

This study involved modeling an existing space with two software packages under a variety of different conditions, and then comparing the results of the simulations against measured values. The software packages selected were Lightscape and Radiance because they are both "physically based" software, i.e., they purport to compute lighting quantities and represent the results as realistically rendered images. Lightscape and Radiance stand in contrast to the more typical "photorealistic" graphics software, which place emphasis on the appearance of the output rather than on the techniques used to derive it. The computed solutions were compared with luminance measurements taken using an IQCam, which is a commercially available photometrically calibrated digital image photometer.[6,9,10]

A drawback of comparing measured and computed values is that lighting visualization software packages may have different limitations than luminance photometers. A further difficulty is in ensuring that measured areas correspond with the same geometric location as those taken from a rendered image.

Software limitations

Perhaps the two most significant limitations of the software are the treatment of material properties and the photometric input. In the case of material properties, the software uses simplifications either to reduce computation time or because the additional complexity would yield diminishing returns. It would be most accurate to describe material surface properties by specifying the spectral reflectance as a function of wavelength and the directional reflectance using a bi-directional reflectance distribution function (BRDF).

Popular visualization software approximates the spectral reflectance with three numbers, one representing each component of red, green, and blue. The spectral power distribution of a light source is simplified in the same way. Given the current state of computer hardware, it is not practical to specify the spectral reflectance of room surfaces or the spectral power distribution of light sources as a function of wavelength. Few researchers and even fewer lighting practitioners have access to computers capable of timely handling the additional complexity.

Radiance will allow a user to specify an arbitrary BRDF. Nonetheless, directional reflectance is more commonly approximated with a number of coefficients specific to the type of material. For example, plastics can be assigned coefficients for specularity and roughness while a dielectric material can be assigned an index of refraction and a Hartman constant. It is not possible to specify an arbitrary BRDF within Lightscape. Instead, Lightscape uses a number of parameters that define a material, including metal or nonmetal, smoothness, transparency, and index of refraction.

The differences in how materials are defined are closely related to the different software algorithms. Radiance is predominantly a ray tracing algorithm; as such it requires little extra computational time to consider a material with an arbitrary BRDF versus say, an ideal lambertian surface. Lightscape is predominantly a radiosity algorithm that initially computes a solution based entirely on diffuse radiative transfer. Lightscape uses the directional material coefficients in a ray tracing post process, i.e., ray tracing is performed after the radiosity solution has sufficiently converged.

The photometric limitations are a consequence of the input files themselves rather than a product of the physically based visualization software. Standard format photometry files contain inadequate information about luminaire geometry and are deficient at near field conditions. One result is that we can not expect the software to automatically model luminaire geometry or to accurately calculate the luminance distribution in the near vicinity of the luminaires. Photometric files containing only a few planes of horizontal data or data at large vertical angular increments could also lead to numerically and/or visually inaccurate simulations. In these cases the software is not entirely at fault.

Measurement limitations

As with all photometers, the IQCam digital photometer is subject to a number of limitations. One example is that the response of the photometer is not exactly the same as the response of the human eye. This deviation of relative spectral responsiveness from the $V(\lambda)$ function

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can be characterized using the error f_1'. Measurement error could also result from a number of other factors, including the meter's UV response, IR response, directional response, temperature dependence, stray light, and the dark current signal within the electronics of the meter. The reader is referred to CIE #69 for a more complete treatment of the issues related to characterizing the performance of luminance meters.[1] Operative characteristics specific to digital photometers have also been discussed elsewhere.[8,10]

Because of the software limitations given above, we would expect the calculated luminance distribution to differ from the true values. And because of the shortcomings of the IQCam, or any other photometer, we would expect that the measured values are really not the true values of luminance either. It follows that one of the fundamental obstacles in validating software (and IQCam measurements), is that the true value of luminance will always be unknown. These limitations make it difficult to perform comparisons in absolute terms; but they do not prohibit relative comparisons.

In consideration of the above, the first objective of this project was to determine if luminance images produced by Lightscape, Radiance, and an IQCam are the same or different. For the reasons given above, it was expected that the different technologies would produce different results. Therefore, the further and more significant objective was to gain insight into how and to what magnitude the separately derived images differed.

Image alignment

Image alignment involves lining up corresponding pixels in separately derived images. The objective, though practically unattainable, is to align images so that all corresponding pixels in separately generated images represent the same point or area of geometric space.

Possible misalignments between images include vertical or horizontal translation, rotation, and/or optical distortions. Pixel misalignments could be global or local. Global misalignments are typically the result of differences in camera position and/or viewing direction within a scene. Local misalignment can result from different placement of objects within corresponding scenes, and are additive with global misalignments. Optical distortions can result in both global and local misalignments. When misalignment occurs, corresponding image pixels do not represent the same geometric location.

The resolution of IQCam, Lightscape, and Radiance images could not be made to match precisely. IQCam images have a fixed resolution of 496 x 288 pixels and a fixed aspect ratio of 1.33:1 (thus individual pixels have a fixed aspect ratio of 1.2949:1). Lightscape renders images using square pixels. Thus, perfect alignment between an IQCam and Lightscape image was not possible without a transformation. Radiance includes an image filtering utility for scaling images and scaling the aspect ratio of pixels. For this project, Radiance images were rendered at the same resolution and aspect ratio as the Lightscape images. Using square pixels, a resolution of 496 x 373 was chosen for the rendered images. With this resolution and 1:1 pixel aspect ratio, the image extents most closely match those of the IQCam.

For good image alignment, it was also important for each of the separately derived images to subtend the same horizontal and vertical angles. The field of view of an IQCam image is dependent upon the choice of lens. A wide angle lens (4.2 mm focal length, fixed focus) was chosen to captures a 56 degree horizontal by 42 degree vertical field of view. The field of view angles specified within the software did not correspond with each other or with the IQCam lens attributes. Therefore, the horizontal and vertical angles were chosen within the software so that the boundaries of the rendered images would visually match each other and the IQCam images.

Also crucial for global image alignment was to maintain the same viewing position and viewing direction across all images. Within the software, it was easy to specify a viewing position and viewing direction. The practical difficulty was in physically positioning the IQCam at the same point, and aimed along the same vector, as was designated within the software. The degree of success was limited only by the ability to physically position the IQCam at the proper position and aimed along the correct vector. Refer to **Table 2** for a summary of the physical characteristics of each image type.

Finally, because the IQCam is a physical imaging device, optical distortions were present in the measured images. Within the limits of this project, neither software rendered optical distortions. Thus, misalignments between corresponding rendered and measured images were present due to optical distortions. During the data collection process, the above items were carefully considered in an effort to reduce misalignment and the associated experimental noise. Still, a statistical method was developed to analyze the degree of success of image alignment. The quality of image alignment has been characterized by performing separate statistical analyses utilizing random samples of different size pixel areas. This concept is further expanded in the ensuing sections.

Methodology

Scenes chosen for comparisons

Twenty-four images of varying degrees of complexity were chosen to compare the software and IQCam under different conditions. There were eight images rendered by Radiance, eight images rendered by Lightscape, and eight images measured with an IQCam. Each set of eight images constitutes all combinations of four different

Table 1—Room surface material properties.

Room Surface	Material	Color	CIE xyY color space Y	x	y	Measured reflectance	RGB color space adjusted for refl. R	G	B
AIR_RETURN	small square grille	matte white	12.7	0.439	0.403		0.390	0.390	0.390
AIR_SUPPLY	painted metal	matte white	23.5	0.436	0.398		0.850	0.850	0.850
CEILING_GRID	painted aluminum	low gloss white	23.5	0.436	0.398	80.4	0.800	0.800	0.800
CEILING_TILE	accoustical ceiling tile	matte white	30.5	0.433	0.402	89.0	0.890	0.890	0.890
DESK_BOTTOM						12.0	0.120	0.120	0.120
DESK_MOULDING	plastic	low gloss off-white	16.2	0.448	0.404	49.2	0.500	0.500	0.500
DESK_TOP	formica	low gloss off-white	62.2	0.439	0.397	50.3	0.500	0.500	0.500
DOC_HOLDER	plastic	low gloss beige	59.0	0.436	0.402	62.4	0.620	0.620	0.620
DOOR	painted metal	matte neutral gray	27.6	0.443	0.404	62.7	0.630	0.630	0.630
DOOR_JAMB	painted metal	low gloss maroon	3.9	0.469	0.382	8.4	0.160	0.040	0.030
FCAB_MAROON	painted metal	low gloss maroon	6.0	0.534	0.362	7.0	0.160	0.040	0.030
FCAB_OWHITE	plastic	low gloss off white	37.7	0.441	0.398	47.8	0.500	0.500	0.500
FLOOR	carpet	matte multi-colored	11.3	0.436	0.401	12.2	0.150	0.150	0.150
LUMINAIRE_REFL	aluminum parabolic baffles	low iridescence matte	59.0	0.418	0.394	19.7	0.450	0.450	0.450
MAG_FILE_BLK	contact paper	low gloss black	2.4	0.440	0.394	4.5	0.050	0.050	0.050
MAG_FILE_BRN	cardboard	matte brown	7.6	0.468	0.412	27.1	0.400	0.240	0.130
PARTITION_FABRIC	fabric	matte off-white	21.4	0.445	0.398	46.0	0.470	0.460	0.440
PARTITION_FRAME	plastic	matte medium gray	22.0	0.477	0.406	33.5	0.340	0.340	0.340
PC_CPU_DK	plastic	matte black	2.7	0.441	0.384	4.5	0.050	0.050	0.050
PC_CPU_LT	plastic	matte cream	47.5	0.441	0.460	62.8	0.630	0.630	0.570
PC_MOUSEPAD	plastic	matte black	2.7	0.441	0.384	4.5	0.050	0.050	0.050
PC_VDT_SCREEN	glass	specular black	9.7	0.423	0.396	12.1	0.090	0.090	0.090
SHELF_MATERIAL	painted metal	low gloss cream	16.2	0.448	0.404	49.7	0.500	0.500	0.500
SHELF_TRIM	plastic veneer	low gloss maroon	4.9	0.534	0.361	6.7	0.160	0.040	0.030
TRASHCAN	painted metal	low gloss medium green	4.4	0.469	0.440	13.1	0.090	0.160	0.030
WALL_TRIM	plastic	low gloss maroon	3.3	0.494	0.378	8.6	0.350	0.080	0.060
WALLS	painted wallboard	light neutral gray	57.1	0.438	0.404	62.7	0.630	0.630	0.630

Final values of R, G, and B were determined using the following procedure:

(1) The chromaticity coordinates for each room material were measured using a Minolta CS-100 Chroma Meter.

(2) The reflectance of each room surface material was measured using a luminance meter and a reflectance standard.

(3) xyY color space was converted to preliminary values of RGB using the equations:

A. Red=(1.73*x) - (0.48*y) - (0.26*(1 - x - y))

B. Green=(-0.81*x) + (1.65*y) - (0.02*(1 - x - y))

C. Blue=((0.08*x) - (0.17*y) + (1.28*(1 - x - y))

(4) Preliminary RGB values were visually adjusted so that screen color would closely match color samples taken from the real space.

(5) The visually matched RGB values were then adjusted for measured reflectance using the equations:

A. Red_corrected=(Red_unc)*((refl/100)*((0.265*Red_unc) + (0.67*Green_unc) + (0.065*Blue_unc)))

B. Green_corrected=(Green_unc)*((refl/100)*((0.265*Red_unc) + (0.67*Green_unc) + (0.065*Blue_unc)))

C. Blue_corrected=(Blue_unc)*((refl/100)*((0.265*Red_unc) + (0.67*Green_unc) + (0.065*Blue_unc)))

luminaires and two degrees of scene complexity. An experimental design matrix is given as **Figure 1**, which also provides a snapshot of the chosen view. The same viewpoint and viewing direction was used for all images; it was chosen to be a typical scene from a sitting position within a cubicle of a partitioned open office. **Figure 1** implies several degrees of complexity which were derivatives of the following two assumptions:

1. A complex scene with complex geometry is more difficult to render than a simple scene with simple geometry.

2. Luminaires with an indirect component are more difficult to render accurately that completely direct luminaires.

It was also expected to be more difficult to perform comparisons on geometrically complex scenes because image alignment becomes more difficult with scene complexity. As it turned out, the data did not provide compelling support for these assumptions. These issues are further discussed later in this paper.

The renderings are of an existing research space at the National Research Council in Canada. One reason this space was chosen was because alternate lighting systems could be easily interchanged, and thus easily measured. Further, the room was quite generic in material finishes and furniture layout. The major room material properties are given in **Table 1**.

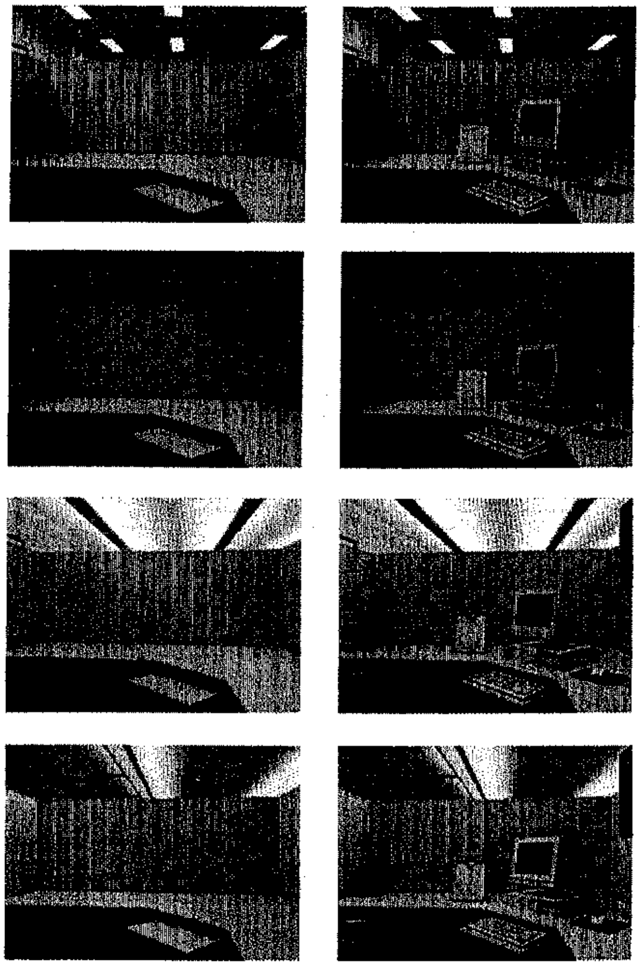


Figure 1—Experimental design matrix. Each cell is representative of three images: a measured image from an IQCam and rendered images from Lightscape and Radiance.

Rendered image generation

The first step in the rendering process involved developing a three-dimensional (3D) model of the scene to be rendered. Tools for generating 3D models include CAD systems, 3D scanners and digitizers, existing 3D model libraries, or text editors.[13] The fastest way to develop a scene is by using existing libraries of 3D objects. This method was not possible for this project, since the renderings would be compared with an existing scene; in order to match existing furnishings, it was necessary to generate all geometry from scratch.

It follows that the first step in the model generation process was to copiously record the dimensions of all the objects that would be included in the rendered scene. This process was performed manually using a pencil, sketches, graph paper, a tape measure, and tracings. Once the items of interest were measured and documented, the objects were built as 3D models using AutoCAD release 12 for DOS. The floor, a ceiling plane, walls, and partitions were also measured and modeled from scratch. All items were located within the CAD model at the same coordinates as the corresponding real items from the existing environment.

The next step in the rendering process was to assign material properties to all surfaces in the scene to be rendered. With some rendering packages this can occur within the CAD software, yet in this project the materials were defined within the rendering software. Since Lightscape and Radiance purport to be physically based, physical measurements were required to aid in the accurate specification of material properties within the software. A Minolta CS-100 Chroma Meter was used to measure chromaticity coordinates (xyY); and the reflectance of each surface was measured using a reflectance standard and luminance meter. The Minolta CS-100 Chroma Meter had a one degree aperture and was factory calibrated and used for less than 30 min prior to this project.

Even with these measured physical properties, it proved to be a very difficult task to accurately specify the material properties within the software. It is quite difficult to define materials so that the surfaces both look realistic and interact with light as they would in the real environment. This issue is discussed in more detail later in this paper.

At this step in the rendering process the surfaces had been physically located and their reflectance properties had been defined both chromatically and directionally. The next step in the process was to specify the photometric properties of the light sources that would be lighting the environment. IES standard format photometry files were obtained from Litecontrol and CFI for use as photometric input. In all scenes, a candlepower multiplier of 0.80 was applied to account for lamp lumen depreciation, ballast factor, and degradation of luminaire efficiency since their initial installation.

Table 2—Summary of image characteristics for the IQCam, Lightscape, and Radiance.

	IQCam	Lightscape	Radiance
Resolution	496 x 288	496 x 373	496 x 373
Image aspect ratio	4:3 (1.33:1)	4:3 (1.33:1)	4:3(1.33:1)
Pixel aspect ratio	1.2949:1	1:1	1:1
Hor. angle subtended	56°	58°	60°
Vert. angle subtended	42°	not specified[1]	45.75°
Camera location[2]	(2323,4225,1110)	(2323,4225,1110)	(2323,4225,1110)
Aiming point[2]	(4686,4451.5,1110)	(4686,4451.5,1110)	(4686,4451.5,1110)
Viewing vector	(2363,226.5,0)	(2363,226.5,0)	(2363,226.5,0)

1. Since Lightscape uses only square pixels, the vertical angle is automatically determined by the horizontal angle and the desired resolution.

2. Coordinates are given in millimeters from the global origin within the computer model.

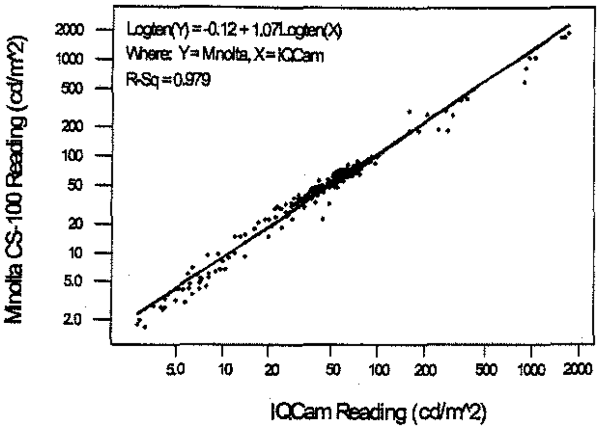


Figure 2—Scatter plot of the measured luminance values along with a linear regression line. Each data point represents the luminance measurement obtained from the IQCam system (horizontal axis) and that obtained from the Minolta CS-100 (vertical axis) for a single location in a given scene.

Once the geometry, materials, and photometry had been set, the model was physically prepared for rendering. The remaining step was to set the processing parameters. As a general rule, the quality of the image and the rendering time will increase as the processing parameters become more rigid. However, since this is not always the case setting the process parameters can be quite a tricky endeavor. It is also important to recognize that setting the parameters too rigorously will generally exhaust system resources. A number of iterative trial runs were necessary to fine tune the geometry, material specifications, and processing parameters.

To help ensure that the software was appropriately utilized, the software developers were asked to review the computer models. The process parameter settings in the Radiance models were reviewed and approved by Gregory Ward of Lawrence Berkeley National Laboratory; Filippo Tampieri of Lightscape reviewed and approved the process parameter settings in the Lightscape models. For this study, the computed luminance at each pixel was just as important as the pictorial representation. Therefore, the final step required was to run a utility program on the final solutions that wrote the computed luminance values of each pixel to an ASCII text file. The Radiance subprogram PVALUE was used to extract luminance values from the Radiance images. The commercial version of Lightscape does not include a utility for extracting the luminance values on a pixel by pixel basis. Lightscape Technologies wrote and provided the utility LSRAYF for use in this project.

Luminance measurement

Luminance measurements were taken using an IQCam digital scene photometer and a Minolta CS-100 Chroma Meter. All measurements were conducted by one of the authors (KH) at Building M24 of the NRC/IRC Montreal Road campus in Ottawa, Ontario. The luminance measurements were taken during the month of October 1996 in the following order: (1) parabolic luminaires, furnished cubicle; (2) parabolic luminaires, empty cubicle; (3) lensed luminaires, empty cubicle; (4) lensed luminaires, furnished cubicle; (5) pendant mounted indirect luminaires, furnished cubicle; (6) pendant mounted indirect luminaires, empty cubicle; (7) pendant mounted direct/indirect luminaires, empty cubicle; and (8) pendant mounted direct/indirect luminaires, furnished cubicle.

The measurements for each luminaire were taken on the same day during the same session. Thus, measurements were taken on four separate days. A few days elapsed between measurement sessions, during which time the lighting system was changed over to the next in the series.

Before recording measurements, the lamps were allowed to warm up for no less than one hour to permit stabilization. Fluorescent T8 sources with a color temperature of 3500K were used throughout. During the warm up time the items in the cubicle were carefully positioned at the same locations as designated within Lightscape and Radiance. The IQCam photometer was carefully located on a tripod at a point in space corresponding to the location of the virtual camera within the rendering software. The IQCam scene capture procedure followed the instructions in Chapter 3 of the IQCam users guide.[6]

Immediately following the IQCam scene capture, a series of measurements was taken using a Minolta CS-100 Chroma Meter. The purpose of taking measurements with a second luminance meter was to authenticate the IQCam data. For the points that were measured as part of this project, the two meters reported luminance values that were not statistically different. **Figure 2** shows a scatter plot of the recorded values along with a linear regression line. For the interested reader, detailed results of the comparison between the two luminance meters have been reported elsewhere.[10]

Data preparation

Statistical sampling and pixel areas

For reasons previously identified, corresponding pixels in corresponding images may not always represent the same area in geometric space. Given this, it was necessary to develop a method for comparing images that addressed this reality. The basic concept of the method developed involved performing the image comparisons using means of pixel areas. In other words, predefined areas of pixels were averaged and the means of these pixel areas were treated as single observations. A representative number (100) of pixel areas was averaged, and

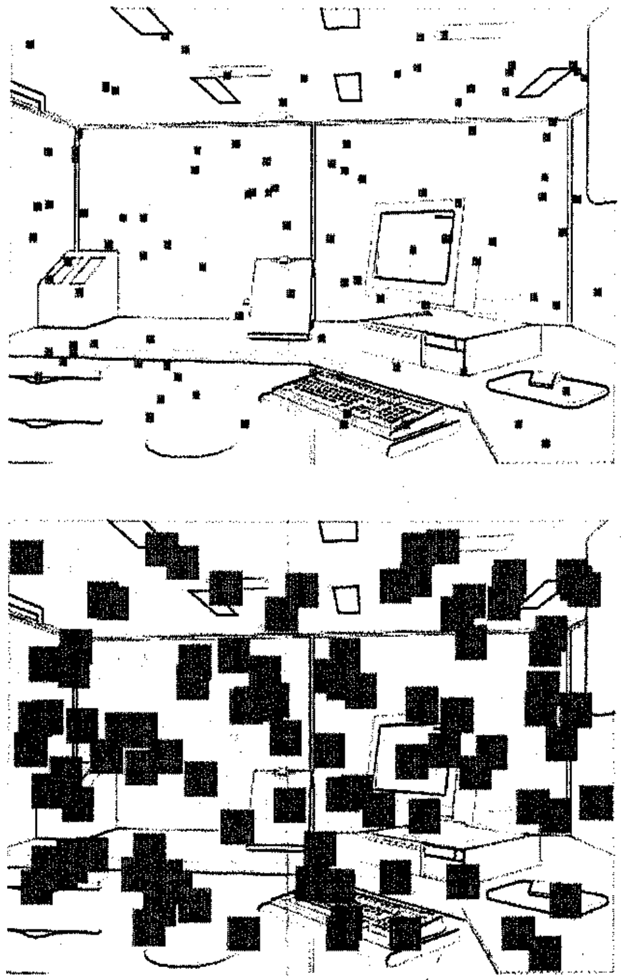


Figure 3—Location of the one hundred randomly sampled pixel areas. The seeds are located at the center of each square.

the resulting sample of means was used as observations for statistical analyses.

The sampling method was a two step process. The first step involved randomly selecting 100 pixels. Since the location of each pixel could be identified by its (i, j) coordinate randomly selecting 100 pixels required the random selection of 100 pairs of (i, j) coordinates. The coordinate pairs were chosen based on the resolution of the rendered images (i.e., 496 x 373). The i coordinates were selected as random integers between 13 and 360 and the j coordinates were selected as random integer between 13 and 483. Since the IQCam image has a resolution of 496 x 288, the i coordinates were transposed to the proper image location. Once selected, the same set of one hundred pixels was repeatedly used as the center points for all sets of observations.

The second step was to use these 100 pixels as the seeds for generating the observations that were used for analysis. Three separate sets of observations were generated for each image, they were different in the pixel sample size used to generate the observations. The three pixel sample sizes chosen for the Lightscape and Radiance images are 9 x 9, 15 x 15, and 25 x 25. Different pixel areas were used for the IQCam images since the resolution and pixel aspect ratio differs from the rendered images. Array sizes of 9 x 7, 15 x 11, and 25 x 19 were used since they approximately correspond to the same image area. Taking into account all of the above, there were a total of 72 sets of observations (3 types of images x 2 degrees of scene complexity x 4 luminaires x 3 pixel areas = 72 sets of observations). A pictorial representation of the small and large pixel areas selected is given in **Figure 3**. Refer to **Table 3** for additional summary information.

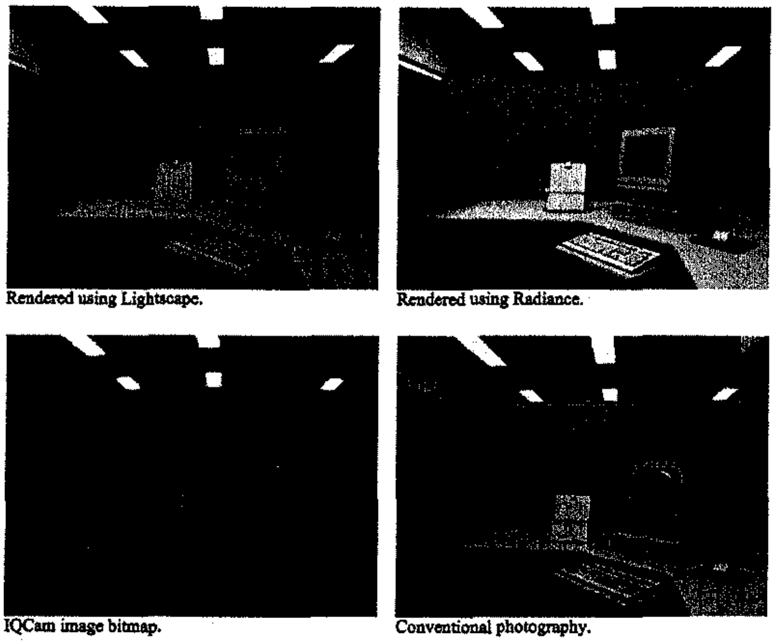
A FORTRAN program was written to automate the process described above. In brief, the program asks what type of image is being sampled, reads in the luminance values for the entire image, computes the mean for the three pixel areas centered at each seed, and then writes the output to an ASCII text file. The output files were written in a format suitable for direct importation into Minitab, which was the statistical software package used for the data analysis.

It was hoped that by using means of different pixel areas as observations for the statistical analyses it would be possible to gain insight into the magnitude of the errors introduced by certain sources of experimental noise, specifically image misalignment and differences in geometry. This method allowed the authors to help isolate differences attributable to differences between Lightscape, Radiance, and an IQCam.

Table 3—Image sample summary information.

	Small pixel area[1]	Medium pixel area[2]	Large pixel area[3]
Lightscape and Radiance images	100 samples of 81 pixels each	100 samples of 225 pixels each	100 samples of 625 pixels each
	≈4.4% of total image pixels	≈12.9% of total image pixels	≈33.8% of total image pixels
IQCam images	100 samples of 63 pixels each	100 samples of 165 pixels each	100 samples of 475 pixels each
	≈4.4% of total image pixels	≈11.6% of total image pixels	≈33.3% of total image pixels

1. Small pixel area: 9 x 9 pixel area for rendered images, 9 x 7 pixel area for IQCam images.
2. Medium pixel area: 15 x 15 pixel area for rendered images, 15 x 11 pixel area for IQCam images.
3. Large pixel area: 25 x 25 pixel area for rendered images, 25 x 19 pixel area for IQCam images.



Rendered using Lightscape. Rendered using Radiance.

IQCam image bitmap. Conventional photography.

Figure 4—Black and white reproductions of the rendered images, an IQCam bitmap, and a conventional photograph for the scene with the lensed troffer and furnished cubicle.

Results

The underlying reason for this project was to qualitatively and quantitatively compare the rendered images with each other, with the IQCam measurements, and with the real space. In essence, there are two ways to assess the quality and accuracy of the renderings. The first method is visual inspection; directly comparing the simulations with each other and with the real space is the most intuitive way to judge visual similarities and differences. Visual inspection can be useful for qualitatively assessing how well material properties (e.g., color and specularity) had been defined and rendered, the accuracy of shadows and penumbras, similarities and differences in geometry, and image alignment.

The second way to assess the quality of the renderings is to analyze the luminance values computed by the software. This is a distinctly different task than visual inspections—it is possible for an image to look quite realistic yet have computed values that are inaccurate. The appearance of an image is highly dependent upon the visual display hardware, including the monitor contrast, brightness, and gamma. Moreover, it is difficult to visually compare a self luminous image with one that is only reflecting light. Consequently, visual inspection is not suitable for evaluating the absolute accuracy of computed values of luminance—an unbiased purely numerical method is required.

Visual comparisons

Figure 4 provides black and white reproductions of the rendered images, an IQCam bitmap, and a conventional photograph for the scene with the lensed troffer and furnished cubicle. Unfortunately, black and white reproductions are only useful for evaluating some visual comparisons. The interested reader is encouraged to contact the author (KH) for the full color electronic versions of the images.

Specific visual differences between Lightscape, Radiance, and the real space are listed:

1. Overall, the Radiance images appear to be grayer (less saturated color) than corresponding Lightscape images. It is unknown why this is the case since RGB reflectance was identically defined in both software packages. Apparently RGB means something slightly different to the two rendering engines.

2. The desktop is somewhat more specular in the Lightscape model than in the Radiance model. Compared to the real space, it appears that neither the Lightscape nor the Radiance desktop was defined with enough specularity. By visual inspection alone, it is thought that the Lightscape desktop has been defined slightly more accurately than the Radiance desktop.

(Comments regarding items 1 and 2: In both Lightscape and Radiance, the spectral nature of reflectance was defined with identical coefficients for RGB reflectance. It was not possible to use the same coefficients for the directional nature of reflectance since they are specified differently in the two software packages. This resulted in a number of inevitable differences between how the Lightscape and Radiance materials were defined. For example, most surfaces were assigned the material plastic, which is a material with uncolored highlights. In Radiance, a plastic is defined by its RGB reflectance, its fraction of specularity, and its roughness value.[12] In Lightscape, a plastic is defined by its RGB reflectance, smoothness coefficient, transparency coefficient, and index of refraction.[7] Since the materials were defined using different coefficients, the parameters were fine tuned through an iterative process of trial and error. The parameters were chosen in an effort to make the rendered images look both like each other and like the real environment.

Setting material properties (RGB reflectance, specularity, roughness, etc.) is a very difficult task for the software user. If an illumination engineer has a device to measure color, it is probably one that measures CIE chromaticity coordinates. More comprehensive measurements could be taken using a spectra-radiometer. Practically speaking however, most lighting practitioners do not have access to these expensive devices. Within the software, the most common way to specify a material color is with RGB reflectance. There are alleged functional equations that purport to convert between RGB color space and CIE color space. The authors have not found these equations to be accurate; in other words, when using these equations the displayed RGB color was not a satisfactory visual match to the measured xyY surface from the real space.

Since the software is intended to be physically based, it seems reasonable that it should be possible to define material color using physically based metrics, rather than specifying color in a language created for visual displays. It would be convenient if the software permitted the user to specify color in either RGB or CIE xyY color space. It is the authors' opinion that it would be simpler to specify material colors in CIE color space.)

3. The Lightscape computer screen was modeled as a faceted 3D surface, and each surface was defined as being perfectly specular. In Radiance, the computer screen was modeled as a true curve (part of a sphere) and was assigned a small amount of roughness. These modeling differences resulted in visual differences between corresponding pairs of rendered images. For example, the computer screen in the ray-traced Lightscape images shows a more pronounced reflected image of the luminaire than corresponding Radiance images. This is especially apparent for the scenes with the lensed troffer.

Further, the monitor itself appears to have been tilted back more in the real space than in the rendered images. This difference in geometry resulted in a larger reflected glare spot in the photograph and IQCam image when compared with either of the rendered images.

4. One of the Lightscape images has a blue cast to it—the rendering of the empty cubicle with the pendant mounted linear indirect luminaire. Ian Ashdown of Ledalite shared a similar experience he had when writing his own radiosity renderer. The C++ code in his algorithm was correct, and yet he too would occasionally get a blue cast to the images. The problem he encountered was that the Microsoft C++ compiler was generating incorrect machine code that caused the program to read the wrong registers during a floating-point calculation. The image would most often be rendered properly but on occasion it would be rendered with a blue cast—it was dependent on the previous state of the register. While a plausible explanation, it is unknown if the problem encountered with this particular Lightscape image is for the same reason.

5. The shadow across the partition in the Lightscape images using the pendant mounted linear direct/indirect luminaire appears to be incorrectly rendered. The shadow boundary is quite distinct in the Lightscape image; this sharp shadow does not appear in photographs, IQCam images, or Radiance images of the same scenes.

6. The parabolic louvers do not appear as they would in the real environment in either Lightscape or Radiance. Ironically, while both software packages are quite good at approximating the appearance of illuminated surfaces, they are comparatively inferior at representing the appearance of luminaire openings.

7. The gradient on the ceiling from the luminaires with an indirect component is different when comparing corresponding Radiance and Lightscape images. The gradient appears softer and smoother in the Lightscape images versus the gradient in the Radiance images. This may be a consequence of the fact that Radiance computes the final RGB values for each pixel without regard to adjacent pixels, while Lightscape utilizes gourard shading.[2] In both cases, the software is bounded by the dynamic range of the computer monitor; which is considerably smaller than the dynamic range of the real scene; for this reason neither Radiance nor Lightscape are exemplary at realistically rendering the gradient on an indirectly lighted ceiling.

8. Since Radiance and Lightscape render based upon a virtual camera, their images have no optical distortions. Conversely, since the IQCam is a physical device with a real lens, IQCam images are optically distorted. This fact inevitably resulted in some degree of image misalignment.

9. The door is in a different location in the rendered images. It is unknown why this occurred because the geometry for both models was identical. More importantly, the door does not appear in the IQCam image.

10. The second row of luminaires can be seen in their entirety in the rendered images, but are cut off by the partition in the IQCam image.

(Comments regarding items 9 and 10: These items suggest that the virtual camera within the computer models was located higher than the IQCam was mounted in the real space. This difference in mounting location contributed to noise within the data.)

Statistical comparisons, image alignment

Individual ANOVAs revealed that pixel sample size was never a significant factor in the comparison of mean luminance ($\alpha \leq 0.05$). This fact alone is a strong indication that image alignment was quite good. Main effects plots further indicated that in the context of this study, the technology used to obtain the luminance values had a considerably larger effect on mean luminance than pixel sample size.[5]

Edwards' test statistic for the homogeneity of the correlation coefficient across pixel sample size was also used for evaluating image alignment.[3,4] Twenty-four test statistics were computed and have been summarized in **Table 5**. As

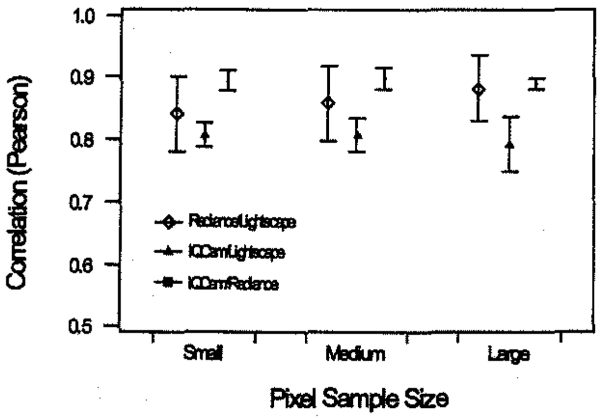


Figure 5—Correlation summary by pixel sample size.

shown in this table, there was not a statistically significant difference in 18 of the 24 cases. At first glance this may seem to indicate that pixel sample size did in fact have a significant effect on the correlation—at least in six of the twenty-four instances. However, the statistical significance is in part an artifact of how the test statistic is computed; in this case the statistically significant differences do not translate to substantive differences.

The computation of Edward's test statistic is such that it is considerably more restrictive when the correlations being compared are very high. For example, the correlations between Lightscape and Radiance for the scene with the parabolic troffer and furnished cubicle are 0.975, 0.984, and 0.989 for the small, medium, and large pixel sample sizes, respectively. With a sample size of 100, the test statistic is 8.33 and null hypothesis that these correlation coefficients come from the same population is rejected—even though there is not a substantive difference between the three values. Further, the correlation coefficients between the IQCam and Lightscape for the scene with the pendant mounted linear indirect luminaire and furnished cubicle are 0.824, 0.854, and 0.886 for the small, medium, and large pixel sample sizes, respectively. With a sample size of 100, the test statistic is 2.67 and the null hypothesis that these correlation coefficients come from the same populations is not rejected—even though the range of these correlations is considerably larger than in the previous example (0.062 vs. 0.014). In both cases, the difference between the correlation coefficients is not substantive.

There are still a number of other ways to gain insight into the quality of image alignment. The mean and standard error of the correlation coefficients are presented for each pixel sample size in **Figure 5**. Although there is not a formal test statistic associated with this figure, it is clear at a glance that the mean and standard error of the correlation coefficients are highly similar at the different pixel sample sizes. Still another way to assess the quality of image alignment is by observing the plots of the correlation coefficient by pixel sample size for each of the eight scenes.[5] In some cases the correlation coefficient will increase with pixel sample size, in other cases the correlation coefficient will decrease with pixel sample size, and in some cases there is no change. This suggests that the small differences that are present are likely resulting from random error rather than from a systematic bias.

Each of these items separately suggests that image alignment was quite good. Taken together, it seems reasonable to conclude that pixel sample size did not result in substantive differences in the results of the comparisons. This important result lends credibility to the remainder of the analyses. Because image alignment was quite good, the differences found among the three technologies can be attributed to differences in the technologies rather than to shortcomings in the analysis itself.

Statistical comparisons, mean luminance

In six of the eight scenes, ANOVA revealed a statistically significant difference between mean luminance (at alpha ≤ 0.05). The exceptions are the two scenes with the indirect pendant luminaire; where ANOVA did not

Table 5—Test of the homogeneity of the correlation coefficient across pixel sample size.

	Simple scene geometry			Complex scene geometry		
CFI flourescent		Lightscape	Radiance		Lightscape	Radiance
1 x 4 ft direct lensed	Radiance	0.317		Radiance	0.366	
	IQCam	4.066	21.419	IQCam	2.689	11.856
CFI flourescent		Lightscape	Radiance		Lightscape	Radiance
1 x 4 ft direct parabolic	Radiance	2.741		Radiance	8.335	
	IQCam	0.580	0.444	IQCam	3.357	3.707
Litecontrol		Lightscape	Radiance		Lightscape	Radiance
indirect pendant	Radiance	33.671		Radiance	38.627	
	IQCam	3.561	0.580	IQCam	2.668	0.815
Litecontrol		Lightscape	Radiance		Lightscape	Radiance
indirect/direct	Radiance	1.026		Radiance	6.249	
	IQCam	0.833	0.543	IQCam	0.310	0.620

Values in the above table are the test statistic for testing the homogeneity of k values of r.[3,4] With three pixel sample sizes the number of degrees of freedom for evaluatning the chi-squared test static is two. Entering chi-squared table with two degrees of freedom, the critical value is 5.992 at alpha = 0.05. The null hypothesis that the correlation coefficients are from the same population will be rejected for test statistics greater than the critical value.

Table 4—Statistical summary of ANOVA, multiple comparisons, and homogeneity of variance.

	Analysis of variance[1]			Multiple comparisons[2]			Homog. of variance[3]
	Method	Pixel sample size	Interaction	IQCam/LVS	IQCam/Rad.	LVS/Rad.	Levene's test
Lensed troffer, empty cubicle	✓	*	*	✓	✓	*	*
Lensed troffer, furnished cubicle	✓	✓	*	✓	✓	*	*
Parabolic troffer, furnished cubicle	✓	*	*	✓	✓	*	✓
Pendant indirect, empty cubicle	✓	*	*	✓	✓	*	✓
Pendant indirect, furnished cublicle	*	*	*	*	*	*	*
Pendant indirect, empty cubicle	*	*	*	*	*	*	*
Pendant direct/indirect, empty cubicle	✓	*	*	✓	✓	*	*
Pendant direct/indirect, furnished cubicle	✓	*	*	✓	✓	*	*

1. Null Hypothesis (H_0): Factor level means are equivalent. H_0 has been rejected for p-values less than 0.05 (alpha ≤ 0.05).
2. H_0: No difference between mean values of luminance. H_0 has been rejected where zero is not contained in the confidence interval (alpha ≤ 0.05).
3. H_0: No difference between population variance. H_0 has been rejected for p-values less than 0.05 (alpha ≤ 0.05).
* Not significant (fail to reject null hypothesis).
✓ Significant (reject null hypothesis).

result in a statistically significant difference between mean luminance. The multiple comparisons provide further insight into where the differences were occurring. For the same set of six scenes, the null hypothesis of no difference between mean luminance is rejected for both the IQCam image versus the Radiance image and the IQCam image versus the Lightscape image. Conversely, the null hypothesis is not rejected for Lightscape versus Radiance.

The null hypothesis is not rejected for any of the paired comparisons for the two scenes with the indirect pendant luminaire. In other words, the data does not suggest that Radiance, Lightscape, and the IQCam arrive at a different value of mean luminance for the two scenes with the indirect pendants. These results have very significant substantive implications. The data suggests quite strongly that in six of the eight scenes, the mean luminance is both statistically and substantively different when comparing the measurements with the computer renderings. Equally interesting is that the mean luminance between Lightscape and Radiance is neither statistically nor substantively different in any of the eight scenes.

Statistical comparisons, homogeneity of variance

The purpose for testing homogeneity of variance was to formally compare the dispersion of luminance values in corresponding scenes. Levene's test statistic was chosen because it is appropriate for continuous data and is robust against the assumption of normality. In six of the eight scenes, the null hypothesis of no difference between population variance was not rejected (alpha ≤ 0.05). The null hypothesis was rejected for the two scenes with the parabolic troffer. Stated another way, for the scenes with parabolic troffers the confidence interval for the standard deviation (σ) was narrower for the IQCam than for the rendered images. Refer to **Table 4** for a summary of the results from the ANOVAs, multiple comparisons, and homogeneity of variance tests.

Statistical comparisons, correlation

Because it was difficult to know how many lumens were actually exiting the luminaires versus what was reported in the manufacturers' photometry files, it was thought that the correlation analysis might provide a better indication of how well the software compared with measured values. The correlation analysis was performed as a way to compare the luminance distributions—this stands in contrast to the previously discussed analyses which were performed largely to assess mean luminance and the quality of image alignment.

Plots of the correlation coefficients have been summarized as **Figures 5–7**—these plots contain an abundance of noteworthy elements.

Referring to these plots, observe that the correlation between Lightscape and Radiance has a considerable

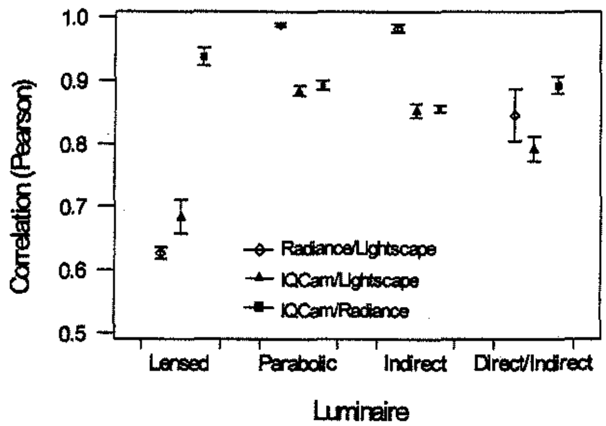


Figure 6—Correlation summary by luminaire type.

range; this is manifested as comparatively long error bars. The fact that the overall mean correlation between Lightscape and Radiance is 0.861 indicates that the computed distributions between the two software packages are generally agreeable. However, the comparatively large range of correlation coefficients indicates that the agreement is quite dependent upon the scenes being compared. Inspection of the correlation coefficients shows that in the worst case (lensed troffer, simple scene, medium pixel sample size) the correlation between the rendered images in just 0.601 while in the best case (indirect pendant, simple scene, large pixel sample size) the correlation is 0.997. This suggests that in some instances Radiance and Lightscape may compute nearly identical luminance distributions while in other instances they may distribute the available lumens very differently.

The mean and standard error bars on the plot in **Figures 5–7** have considerable practical implications. It is clear from this plot that on average, and within the context of this project, the correlation between Radiance and the IQCam is higher than the correlation between Lightscape and the IQCam.

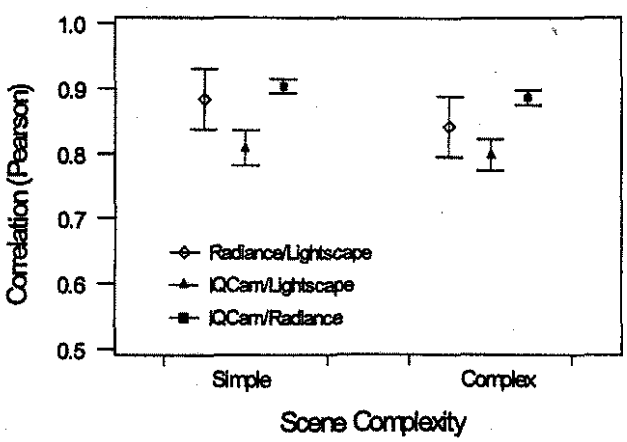


Figure 7—Correlation summary by scene complexity.

Figure 6 is a correlation summary by luminaire types. This figure demonstrates that different photometry affected the different technologies in different ways. There is not a clear-cut reason why the correlations were so low for the scenes with the lensed troffer and so high for the scenes with the parabolic troffer and indirect pendant. The data suggests that the technologies will perform differently from each other in different photometric situations.

Figure 7 is a correlation summary by scene complexity. This figure demonstrates that, within the limits of this study, scene complexity had only a marginal effect on the correlation between technologies. This may indicate that the difference between "simple" and "complex" as chosen for this study was not large enough to reveal an effect.

General discussion

The specific scenes and luminaires chosen were selected in an effort to test the software under what was thought to be varying degrees of complexity. It was thought that the software would have more difficulty rendering a complex environment versus a simple environment, and that is would be more difficult to render a scene with luminaires containing an indirect component. This was not suggested by the data. In the eight scenes that were compared, there were certainly differences in the degree of agreement. Because no distinct trend was observed across the eight scenes, it appears that these differences are more attributable to peculiarities of the separate technologies than to scene complexity or luminaire type.

The fact that there is not a significant difference between mean luminance in any pair of Lightscape and Radiance images is not surprising. With both software packages, the authors had precise control over how many lumens were sent into the environment. The quantity of lumens is simply a function of the photometry files and the multiplying factor; and it is a fact that the input photometry and the multiplying factor were identical for both sets of simulations. The fact that the correlation coefficient between the two software packages range from 0.601 to 0.997 indicates that the manner in which the different software computes the luminance distribution is plainly different. Simply put, the data implies that while Radiance and Lightscape start and finish with the same number of lumens, they may distribute these lumens on the room surfaces in a different way.

Clearly, the three technologies are different in interesting ways. This naturally leads to inquiring about which technology is most correct. With respect to mean luminance, the software computed a higher mean than was measured with the IQCam in every instance. Mean rendered luminance ranged from 9.1 percent to 50.9 percent higher than mean measured luminance. The notion that the measured values are nearer to reality than the computed values seems to be supported by the good agreement between the IQCam and a Minolta CS-100 Chroma Meter.[10] Although speculative, it is the authors' opinion that the IQCam measurements are more representative of what was happening in the space than the computed simulations.

Mean luminance, however, is only one component of this study. Because we did not know with certainty the quantity of lumens exiting the luminaires, it is at least equally meaningful to draw conclusions based on correlation. The correlation analyses reveal that, overall, the three technologies were performing similarly. Yet, there are subtle differences that are quite important.

The correlation between Lightscape and the IQCam ranges from 0.584 to 0.916 while the correlation between Radiance and the IQCam ranges from 0.843 to 0.968. If the IQCam measurements are accepted as our best representation of reality, the data suggests that Radiance did a better job than Lightscape at simulating this reality within the limits of this study. The very low correlation of 0.584 between Lightscape and the IQCam for the lensed troffer and empty cubicle is also troublesome. It is unknown under what conditions a poor match like this will occur, especially since it was thought that this scene would be the simplest to render. This wide range of correlation coefficients tends to undermine the authors confidence in Lightscape's ability to accurately compute luminance distributions. Conversely, the lowest correlation between a Radiance and IQCam image is 0.843, demonstrating that even in the worst case Radiance and IQCam images still had acceptable correlation. This tends to support Radiance's ability to accurately compute luminance distributions.

Future work

This project had the underlying objective of formulating an overall picture of the software's global accuracy. The authors intentionally ignored the importance of individual surfaces by performing the analyses on randomly chosen pixel samples. This was considered to be a necessary first step toward evaluating the software's overall credibility. For a lighting designer, certain regions of any given image may be of greater importance than others. It would be a useful endeavor to first identify the parts of an image that are important, and then perform a focused comparison on these specific regions. This type of study could be designed to evaluate how well the different software simulates specific scene elements.

For example, suppose an image contained a computer monitor and that reflected glare on the monitor has been identified as an important aspect of the simulation. The maximum intensity, shape, and area of the highlight displayed by each technology could be evaluated and compared. This type of study would have the potential to identify subtle yet important differences between the technologies.

A separate follow-up study that could be performed is one with the specific objective of isolating where the software is failing. In this type of study, it would be necessary to perform a systematic series of simulations. The simulations could be contrived so that the final luminance distribution could be calculated beforehand based on pure theory. The simulations would be devised in such a way as to isolate specific components of the simulation. Some examples of elements of the software that could be isolated include; the direct flux calculation, the interreflected calculation, specific material types, and color.

Summary and conclusions

To reiterate, the first objective of this study was to determine if statistical and/or substantive differences exist between luminance images produced by Lightscape, Radiance, and an IQCam. Further, we had hoped to gain insight into how and to what magnitude the separately derived images differ. These issues were addressed by developing luminance images of as identical as possible image planes using the three different technologies. The final images were then visually compared and subjected to a numerical analysis.

Visual and numerical differences were found among the three technologies. The findings are summarized:

1. Within the limits of this study, both Lightscape and Radiance were found to be quite successful at simulating the appearance of an architectural scene.

2. Visual differences between Radiance and Lightscape images include; color differences, differences in specular appearance, small differences in shadows and shadow boundaries, the appearance of the gradient on an indirectly lighted ceiling plane, and luminaire reflections in a computer screen.

3. In all eight scenes, the mean luminance computed by Radiance and Lightscape was higher than that measured with the IQCam; in six of the eight cases the difference was statistically significant.

4. The correlation between Radiance and IQCam images was consistently higher than the correlation between Lightscape and IQCam images; while the correlation between Radiance and Lightscape images was quite variable across the different scenes.

5. Caution should be exercised if the luminance values computed by either Lightscape or Radiance will be used to make design decisions.

6. Within the context of this study, if IQCam measurements are accepted as our best representation of reality, the data suggests that Radiance will simulate this reality better than Lightscape.

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