Colour accuracy in computer simulations for the study of illumination phenomena

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Abstract

Rendering packages such as RADIANCE [1] are used by visual psychophysicists [2-10] to produce complex stimuli for their experiments, tacitly assuming that the simulation results accurately reflect the light-surface interactions of a real scene. By comparing simulation results with their physical real world counterparts we show that RADIANCE can be used to accurately simulate the luminance and colour of real scenes. In the second part of the paper we show, how RADIANCE can be used to study and analyse specific illumination phenomena such as mutual illumination, which is the indirect illumination due to light being reflected by surfaces in a scene. Psychophysical [11, 12] and computational studies [13, 14] have postulated that mutual illumination may provide cues for colour and shape perception.

Comparison of real versus simulated scenes

The calculation accuracy of a rendering package depends on how well the laws of physics are comprised by the simulation program. Within the computer graphics community, extensive validation of new rendering algorithms is a topic of current interest [15-17]. The assessment of the calculation accuracy varies. For very simple scenes the results of a simulation can be compared to the analytically determined solution of the lighting equations [18]. Other possibilities are either to compare behaviour differences for rendered images versus real objects [19] or to compare the results of a simulation with measurements from a real scene [16, 17, 20-23]. RADIANCE has been subjected to validation studies from within the architectural and lighting community [18, 22, 24]. These studies focus on luminance accuracy and work with error margins of +/- 20%, the standard in the industry [25]. For a review on verification of rendering algorithms see also [26].

Real Scenes

Our real scenes were set up in a lighting booth, which consisted of a custom designed 2.2 x 2.2 x 2.2 m frame built from aluminium scaffold tubing. Three walls and the ceiling were covered by black wool cloth to provide non-reflective surfaces. Low voltage spotlights could be hung at any point from the ceiling.

With a spectroradiometer we measured the colour signal reflected from surfaces in our scenes, to which we will refer as measured values. We also measured the intensity distributions of the illuminant, the reflectance of the materials in the scene and the geometrical layout. We set up two scenes: a) a simple illumination scene, in which a Macbeth ColorChecker® card was directly illuminated and b) a complex illumination scene, in which a white cylinder was horizontally placed on a green card. The green card was directly illuminated and produced a colour gradient on the white cylinder due to mutual illumination (for a photograph see Figure 3a). In a) we measured the colour signal of four colour patches and in b) we measured the vertical colour gradient on the cylinder in 1-cm steps.

Simulated Scenes

Each scene in our lighting booth was simulated in RADIANCE using one of three possible colour-coding methods: RGB, sRGB and spectral rendering. The latter was implemented by an N-step algorithm [7]. For N = 3 the spectrum is divided into three consecutive, equally spaced wavebands ([380-510 nm], [515-645 nm] and [650-780 nm] in our case) and the average value for each of the wavebands is calculated and used as the corresponding colour descriptor. For N = 9 the spectrum is divided into nine wavebands and nine average values are calculated. To implement a 9-step approximation in RADIANCE, three images are rendered, each image accounting for a different part of the spectrum. Given our measurements, N = 81 is the best possible approximation and involves rendering 27 images. To make a single displayable image, the information of N images has to be collapsed into a standard three-channel RGB image. The principle of this algorithm is related to hyperspectral imaging where one image is taken for each waveband, resulting in N images for a scene. Together these N images carry the full spectral information for each single pixel in the image. We compared the output values of the simulated scene with the measurements from the real scene at corresponding locations.

Results

To compare our simulation results with the measured values, we converted the data to CIELAB and computed ΔE (this comparison is based on calculated values only and no attempt has been made to display the simulated images). For the simple scene, RGB and sRGB colour-coding yielded ΔE values of 9.5 and 6.3, which are relatively low values, but above the perceptual threshold of 1 (Figure 1a). For the spectral colour-coding method we used N=3, 9, 27 and 81 wavebands. This method lead to an improved colour signal – and hence lower ΔE values – when more than three wavebands were used (ΔE values for N=3: 32.8, N=9: 4.9, N=27: 1.0, N=81: 0.8). For the complex scene, RGB and sRGB colour-coding yielded ΔE values of 7.2 and 9.4. For the spectral colour-coding method, the ΔE value did not improve with more wavebands and stayed at about 8 (ΔE values for N=3: 38, N=9: 8.7, N=27: 8.2, N=81: 8.4; Figure 1a). In Figure 1b and c we plotted the simulation results of the complex scene together with the values measured in the real scene in the CIE chromaticity plane and for the luminance component, respectively. While the recovery of the luminance profile (Fig. 1c) of the complex scene is almost perfect for the spectral and very good for the RGB and sRGB colour-coding method, the recovery of the chromaticity profile (Fig. 1b) is worse. The RGB- and sRGB-based profiles

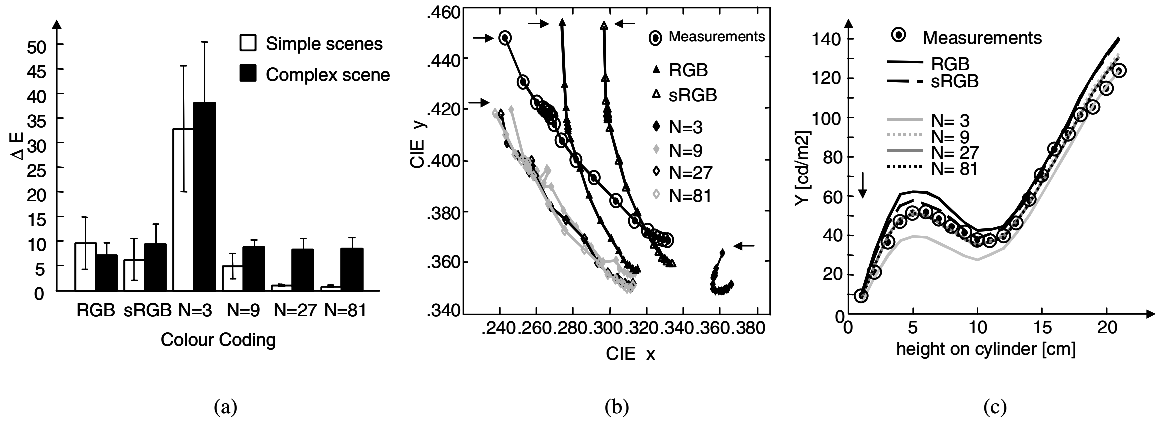


Figure 1. : Comparison of simulation results with measured data for the simple and complex scene. The arrows indicate the values for the point where the cylinder touched the green card. For details see text.

cross the true profile, whereas the spectrally-based profiles lie on top of each other parallel to the true profile. Figure 2 shows the recovery of the complex scene using different colour coding methods.

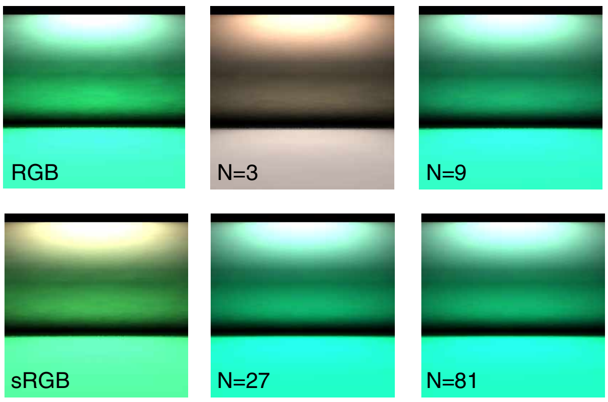


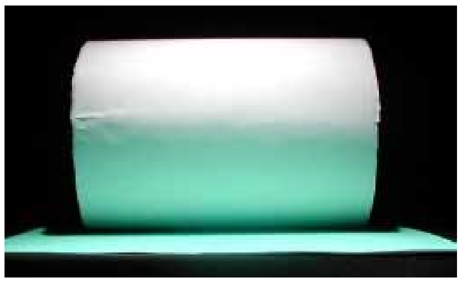
Figure 2: Simulation results of the complex scene.

Given our scenes, with only a few objects and with verified Lambertian surface properties, RADIANCE's calculation results are shifted in colour space. Potentially, this may pose a problem for a visual psychophysicist. Currently, there is no better simulation alternative for a visual psychophysicist to achieve physical realism (i.e. the simulation result providing the same visual stimulation as a real scene) than by combining a spectral rendering method with RADIANCE [27].

Analysing illumination phenomena: mutual illumination

While the calculated simulation results of RADIANCE may not be absolutely accurate, they are close enough to physical accuracy to allow studying illumination phenomena in more detail. In this part of the paper we looked at mutual illumination, which arises from light reflected between surfaces. Our study scene was a corner made from a white and a green card hinged at 70 deg. The green card was illuminated at an angle of 30 to 44 deg (0 deg = direct illumination of green card, 90 deg = direct illumination of white card). This produced a colour gradient on the white card (for a photograph see Figure 3b). The gradient is a mixture of illumination effects. The colour gradient is solely due to inter-reflections between the two hinged cards, whereas the luminance gradient is a combination of direct and indirect illumination caused by the orientation of the card with respect to the light source and by inter-reflections. How do these components of the gradient change as the illumination angle changes and what happens when the hinge-angle of the cards are changed?

a)



b)

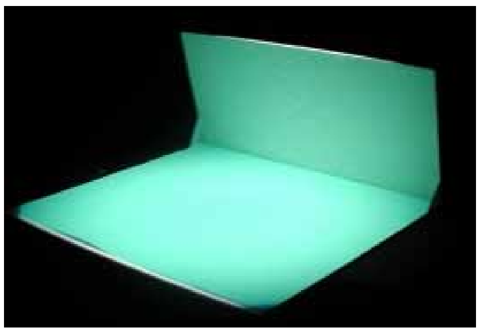


Figure 3: a) Photograph of the complex scene (a white cylinder on a green card). b) Photograph of the 70 deg corner scene (a green card and a white card slanted by 70 deg). The colour illustrations here may not reproduce accurately when printed or displayed on uncalibrated monitors.

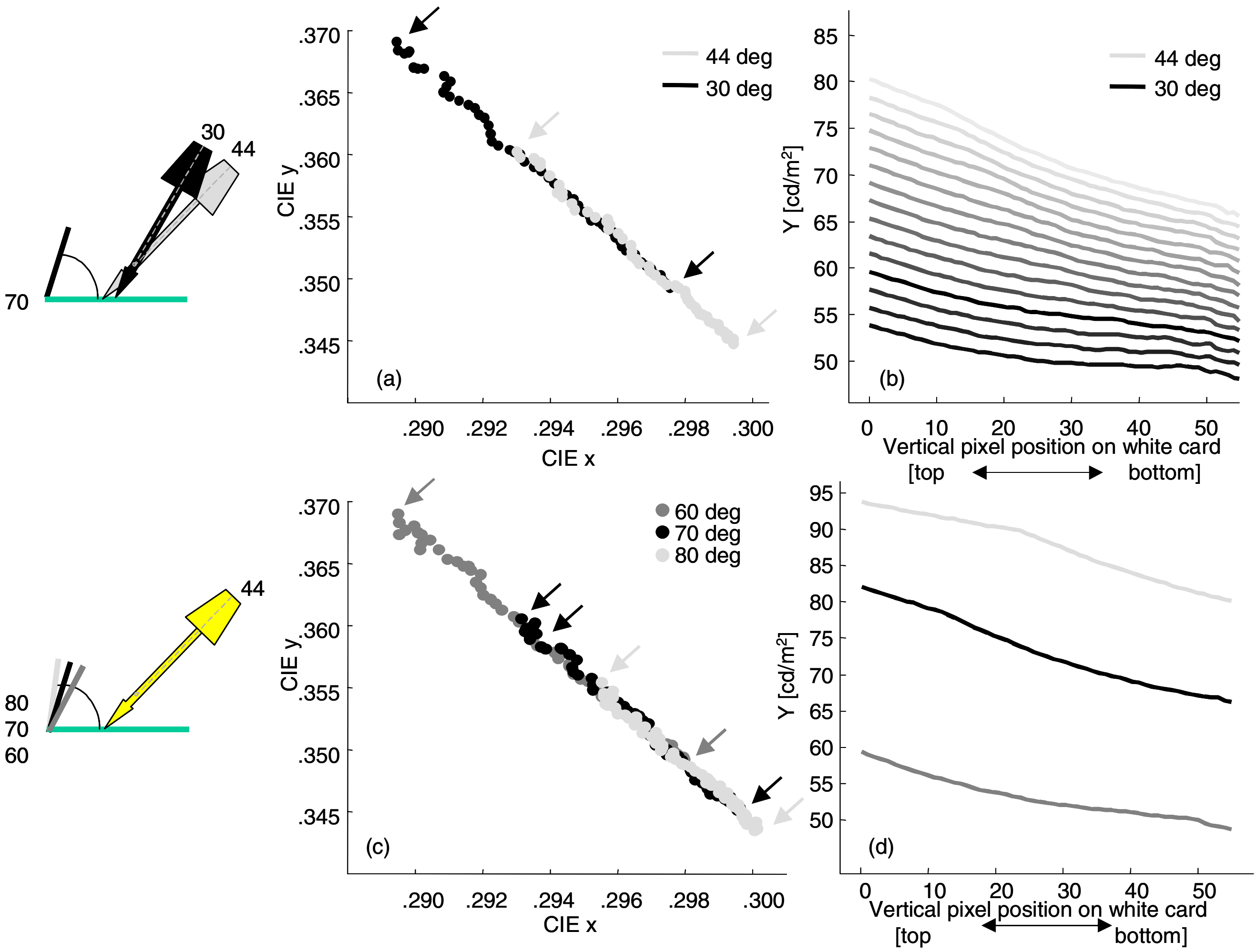


Figure 4: Analysing mutual illumination in the corner scene. The arrows indicate the first and last value of the vertical profile. For details see text.

We simulated this corner scene in RADIANCE using spectral rendering with 81 wavebands for 15 different illumination angles (30 - 44 deg) and two additional hinge angles (60 and 80 deg). To assess the effects on the gradient in a more systematic manner we approximated each gradient by its vertical profile. The vertical profile of the gradient was calculated by averaging horizontally over five central columns, running up from the bottom to the top of the white card. A profile contained 55 values, with each value representing the mean of 5 pixels in a single row at the corresponding vertical position. Figures 4a and b show the chromaticity and luminance profiles for illumination angles from 30 to 44 deg. The scatter plot of the chromaticity profile for a given illumination angle forms a straight line in the CIE chromaticity plane, which shifts systematically towards the more neutral ('whiter') region of the plane as the illumination angle increases. This pattern results from the fact that the chromaticity values of all pixels on the white card are linear mixtures of the two 'direct-illumination-only' chromaticity values of the white and green cards. The luminance profiles, plotted as a function of spatial position, are linear, with negative slopes from the top to the bottom of the white card. As the illumination angle increases, the slopes of the luminance profiles become steeper and the overall luminance level (the offset) increases.

The effect of a constant light source position with a change in the hinge-angle of the corner is similar. Chromaticity and luminance profiles for 60-, 70- and 80-deg-corners with an illumination angle of 44 deg are shown in Figures 4c and d. The chromaticity profiles for different hinge angles share a common straight trajectory in the CIE chromaticity plane and the linear luminance profiles differ in their offsets. The 80-deg-corner has the brightest luminance profile and the 60-deg-corner the lowest.

If the white card is replaced by a white cylinder (= complex scene in first part of paper) then the resulting chromaticity profile is close to a straight line in the CIE chromaticity plane and the luminance profile becomes non-linear (Figures 1b and c). In summary, chromaticity profiles of colour gradients are determined by the colours of the involved objects and lights, and the luminance profiles convey information about geometry, be it illumination angle or object shape.

Conclusion

We have shown that RADIANCE can be used to accurately render colour and luminance signals when a spectral rendering method is employed. Using only spectral information has the added advantage that all calculations are independent of display devices. RADIANCE, therefore, offers the possibility of studying illumination phenomena, such as mutual illumination in a detailed and systematic manner. This is particularly useful for complex scenes that do not yield an exact analytical solution or are impractical to construct. Additionally, if the images generated by RADIANCE can be displayed on a monitor (or similar device) it becomes a powerful tool for psychophysical research into human colour and shape perception.

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