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Luminance in Computer-Aided Lighting Design

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1. Introduction

Traditionally, the lighting engineering community has emphasized illuminance, the amount of light reaching a surface, as the primary design goal. The Illuminating Engineering Society (IES) provides tables of illuminances for different types of tasks which lighting engineers consult in designing lighting systems [Kaufman81]. Illuminance has proven to be a popular metric because it corresponds closely to the amount of energy needed to light a building as well as the initial cost of the lighting system. Perhaps more importantly, illuminance is easy to calculate, especially in simple unobstructed spaces with direct lighting. However, illuminance is not well correlated with visual performance, which is the real reason for installing a lighting system in the first place.

Visual performance is a psychophysiological quantity that has been tied to physical quantities such as contrast, size and adaptation level by subject experiments [Cobb28] [Rea86]. These physical quantities can be approximated from illuminance using a host of assumptions about the environment, or derived directly from the distribution of luminance. Luminance is the quantity of light traveling through a point in a certain direction, and it is this quantity that the eye actually "sees". However, the difficulty of calculating luminance for common tasks has made it an unpopular metric. Despite its importance to lighting design, luminance is rarely used because there is a lack of the necessary computational tools.

In this paper, we will demonstrate a computer calculation of luminance that has significant advantages for lighting design. As well as providing an immediate evaluation of visual quality for task performance, less quantifiable factors such as aesthetics can be studied in synthetic images produced by the program.

2. Luminance Calculation

Virtually any lighting metric can be derived from luminance, the density of visible light passing through a point in a given direction. Illuminance, for example, is equal to the integral of luminance over a cosine-weighted (ie. projected) hemisphere. Luminance itself can be calculated from luminance by a similar integral (Equation 1).

Conceptually, a luminance value can be thought of as an infinitesimal beam or "ray" of light. Using this analogy, a ray's value is equal to an infinite sum of other rays multiplied by the reflectance of the surface in each direction over the projected hemisphere.

This observation leads to a practical approximation of luminance using a finite sum of rays, where a ray is merely a starting point and direction in a geometric model. The intersection of each ray with the model is computed, and other rays emanate from intersections in a recursive evaluation [Whitted80]. This process is only carried out to a

$$L_r(\theta_r, \phi_r) = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} L_i(\theta_i, \phi_i)\, f(\theta_i, \phi_i; \theta_r, \phi_r) \cos\theta_i \, \sin\theta_i \, d\theta_i \, do_i$$

where: $L_r(\theta_r, \phi_r)$ = luminance radiated in direction (θ_r, ϕ_r)

$L_i(\theta_i, \phi_i)$ = luminance incident from direction (θ_i, ϕ_i)

$f(\theta_i, \phi_i; \theta_r, \phi_r)$ = bidirectional reflectance distribution function

θ's are polar angles from surface normal

ϕ's are azimuth angles in the surface plane

finite depth, hence the entire calculation is finite. Note that this method follows the path of light backward -- to compute a ray value, other rays are traced until enough sources of direct and indirect illumination are found.

The key to accuracy in such a ray tracing luminance calculation is locating important contributors to the integral in Equation 1. The model geometry can be used to find direct paths to light sources where the luminance value is often large, and follow specular rays where the reflectance distribution function is highly peaked [Ward88.1]. Techniques exist for the efficient calculation of diffuse and other contributions as well [Kajiya86] [Ward88.2].

A ray tracing luminance calculation can simulate a wide variety of light interactions, using virtually any geometric model. Diffuse and specular reflection and transmission can be calculated in scenes containing thousands (even millions) of geometric primitives, including polygons, spheres, cones, and other curved surfaces. By calculating luminance, other lighting metrics can be derived such as candlepower, illuminance, and contrast rendering factor.

3. Sample Applications

Two examples were chosen to demonstrate the value and generality of this type of luminance simulation. The first example is a simple rectangular office space to which we will add partitions and furniture to mimic a progressive design process. This will show the importance of model detail on the prediction of light levels and visibility. The second example is an outdoor sculpture made of specular and transparent materials whose lighting will depend more on aesthetic issues than light levels. This will show how a luminance simulation can be used to evaluate a design for which conventional computer models are useless.

3.1. Office Space

In this example, a 92 by 51 foot rectangular room has a 10 foot ceiling. The diffuse reflectances of the ceiling, walls and floor are 80%, 50% and 25%, respectively. Seventy-two 2 by 4 foot two-lamp lensed fluorescent fixtures were arranged on a uniform grid with 7 rows and 12 columns designed to provide an illuminance level around 750 (maintained) lux at the workplane. The number of fixtures required to deliver this level was calculated using the standard IES room cavity ratio method [Kaufman81]. The initial layout and computed light levels along the length of the space are shown in Figure 1.

Two rows of 16 paired cubicle partitions each were then added to the model space as shown in Figure 2. The average and standard deviation of illuminance at each desk in the second row of cubicles were calculated from 18 points arranged in two evenly distributed rows on each desk. Note that the partitions cause the light levels at the desk surface to drop by about a factor of two compared to the empty space, and that uniformity is severely compromised. The effect of partitions on workplane illuminance has been investigated empirically [Siminovitch87] and can be approximated analytically [Ballman87]. However, the analysis of partitions is not practiced widely due to the lack of computational tools for accurately assessing their effect. Using a general luminance calculation, all obstructions (not just rectilinear partitions) can be considered, requiring only a few minutes to compute.

To create a more uniform distribution of light on the cubicle desks, a second luminaire layout was designed with the fixtures directly over the partition walls as shown in Figure 3. The graph shows the new average and standard deviation of illuminance on the desks in the second row of partition cubicles. With this arrangement, each cubicle has two halves of a fixture on either side of its desk, which tends to minimize body shadowing and veiling reflection and produce high uniformity. To reduce the lighting of the central aisle between the partition rows, single lamp fixtures were used on either side. Four fixtures were used at the end corridors to provide acceptable lighting on the perimeter. The total lamp count for this arrangement is 96, down from 168 for the first design -- an energy savings of 43%. The graphs in Figure 4 show illuminance values at 18 sample locations on a representative desk under the two lighting conditions. The light levels of the nine sensors in the row furthest from the occupant is nearly as high as those in the near row.

The real power of a luminance simulation comes into play when the user demands a more intuitive representation of the light distribution on the desks. Figure 5 compares luminance maps (images) of the same desk under each fixture arrangement. These images give the shadows and brightness ranges in full detail, eliminating the need for guesswork. In an interactive display, individual luminance values can be extracted from the finished calculation at selected image locations. This combination of numerical and visual information is extremely useful to a lighting designer, comparable to taking a light meter into a finished space -- without first having to build it.

By adding recognizable objects to the model, further detail comes out of the calculation, such as the effect of light distribution on task visibility. Figure 6 is the same as Figure 5 with books and other miscellany added to the model. Suddenly the images take on real meaning, and unquantifiable considerations such as visual quality and atmosphere are accessible from what is still a computer calculation. With a simple change in view, one can evaluate the visibility of a reading task in this environment (Figure 7), and the dependence on view angle and surface specularity is reflected by the simulation in a form that is immediately perceptible.

Task lighting will often improve visibility substantially for a modest investment. A complementary pair of compact fluorescent fixtures was added at each desk to show the effect of one type of task lighting. Figure 8 shows the light distribution when the ambient light is provided by the second overhead layout.

This example has demonstrated some important lighting issues that can be addressed in a luminance calculation, such as uniformity, shadowing, glare and visibility. At each level of detail, new information was produced by the simulation, allowing the designer to optimize his lighting solution without resorting to physical models or uncertain assumptions. Although some of these questions could be answered by conventional calculations, the work involved is daunting and the results are less intuitive. Next we will look at a design problem where the usual lighting metrics simply do not apply.

3.2. Exterior Sculpture

In this example, an acrylic sculpture with a metallic base near the center of an atrium office structure is to be illuminated at night. The choice of lighting is primarily an aesthetic one, although there might be specific goals such as keeping a proper balance between the brightness of the building and the brightness of the sculpture.

Three sources of illumination were considered. The first source is general area lighting consisting of four diffuse emitters located near the corners of the glass roof structure covering the square atrium space. The appearance of the sculpture illuminated by this light is shown in Figure 9. The second source of illumination is two floodlights located slightly more than halfway up the walls in opposite corners of the atrium. The illumination due to these sources is shown in Figure 10. The third source of illumination is a ring of three floodlights surrounding the base of the sculpture at relatively close range. The illumination due to these sources is shown in Figure 11.

Once these components have been computed, it is a trivial operation to combine them using different intensities and color combinations. This operation is equivalent to using different wattage and color light sources in each position. Figure 12 shows a reasonable balance between general and overhead flood lighting. Figure 13 shows a balance between general and flood lighting from underneath the sculpture.

From this calculation the lighting designer obtains an unambiguous prediction of the appearance of each candidate solution.

Only with a luminance calculation can a designer perform this type of aesthetic analysis, and thereby reduce the need for experimentation and the probability of error.

4. Conclusion

Because visual performance is the ultimate purpose of lighting, it should also be the ultimate metric in lighting simulation. A general calculation of luminance can predict task visibility in any given lighting environment, and present this prediction in a visual form that is immediately understood by experts and laymen alike. The key to accuracy in a luminance calculation is the faithful modeling of light behavior, including shadows, specular and diffuse reflection and transmission, and critical detail of the visual task itself. We have presented a ray tracing calculation that follows light backward to consider all these effects simultaneously in a simple and natural fashion. The technique has been applied to a variety of environments with great success, and we have shown two representative examples.

Luminance calculation moves lighting analysis from the simple box world of diffuse illumination to the real world with all its visual complexity. Unlike improvements in other forms of simulation, enhancements to lighting prediction lead to simpler design evaluation through a direct link to the most sophisticated analysis system of all, human vision.

5. Acknowledgements

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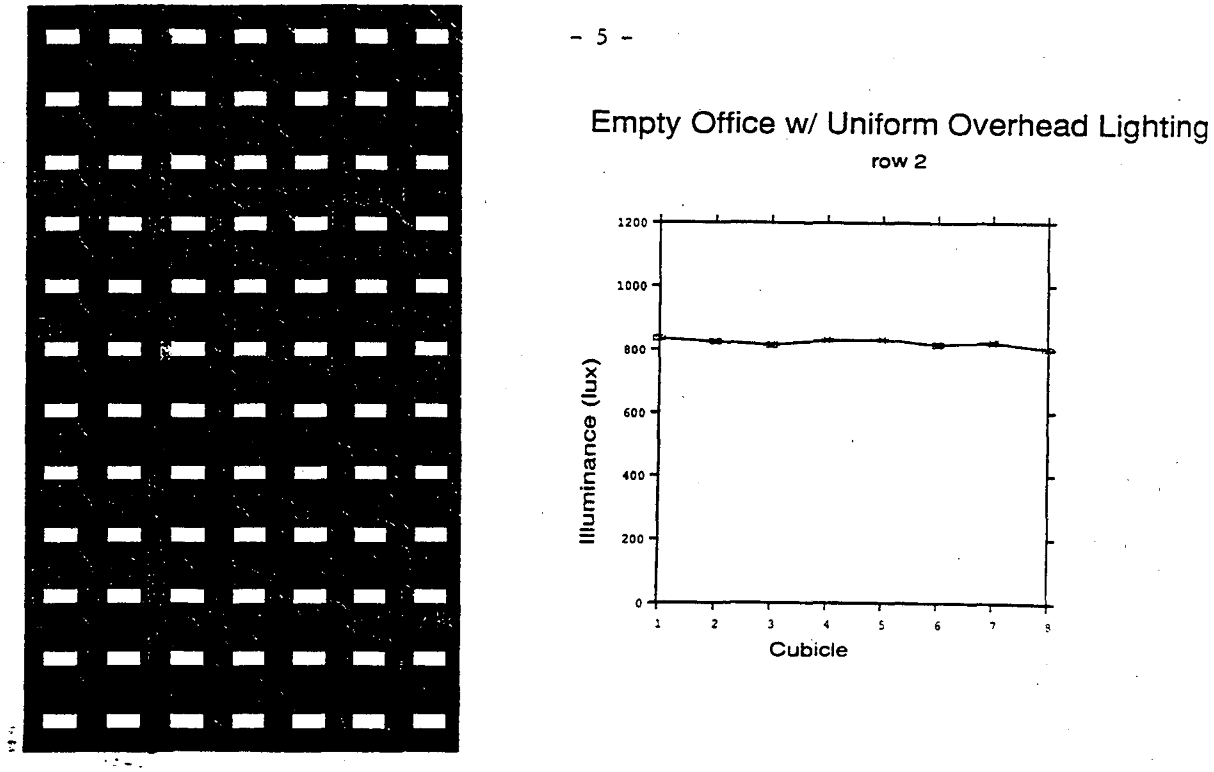

Figure 1. Initial luminaire layout for office space and corresponding light levels.

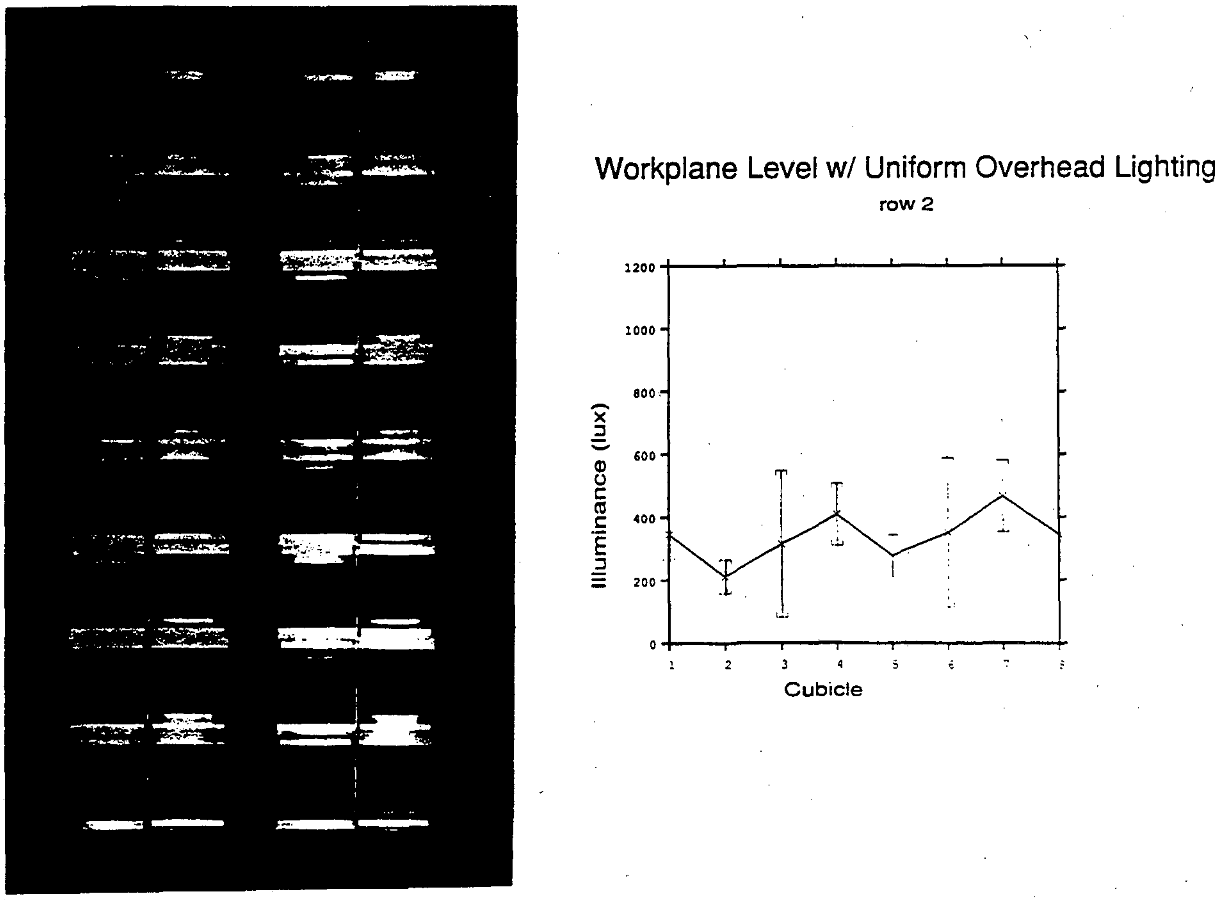

Figure 2. Partitions added to space and their effect on light levels with initial layout.

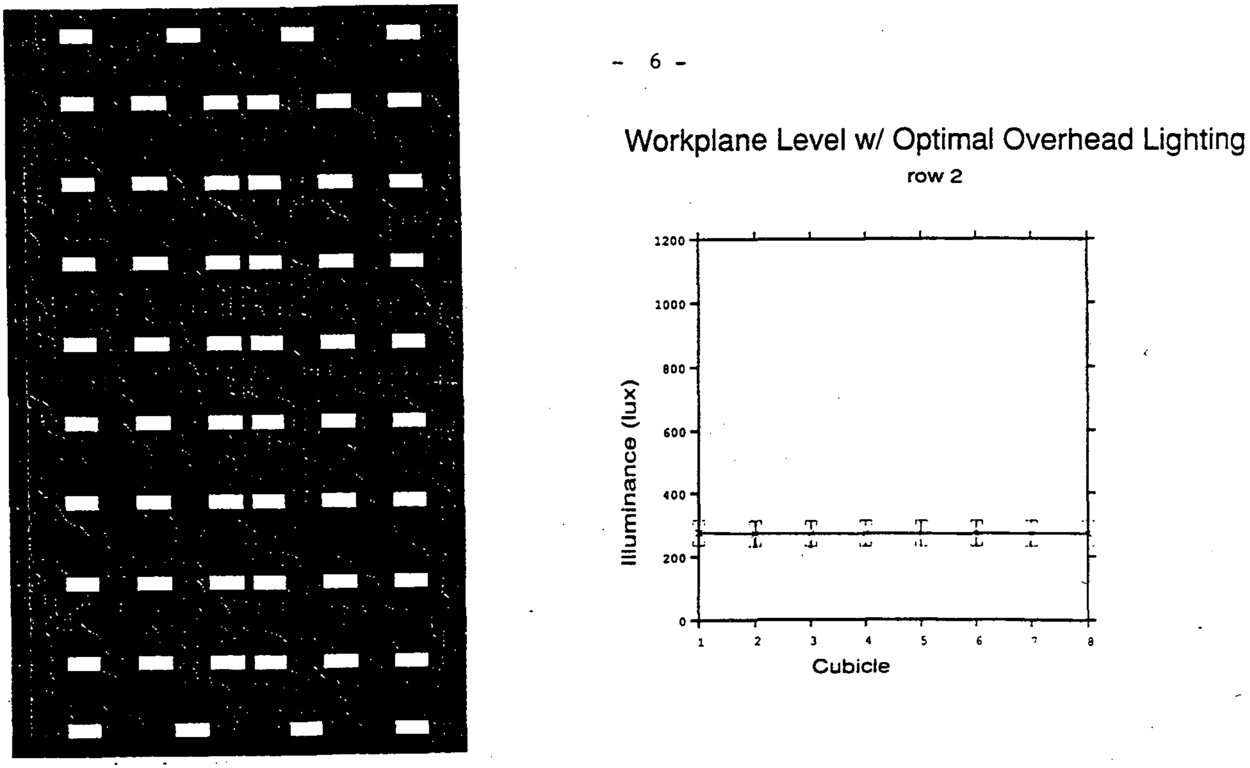

Figure 3. Optimized luminaire layout for office space with partitions.

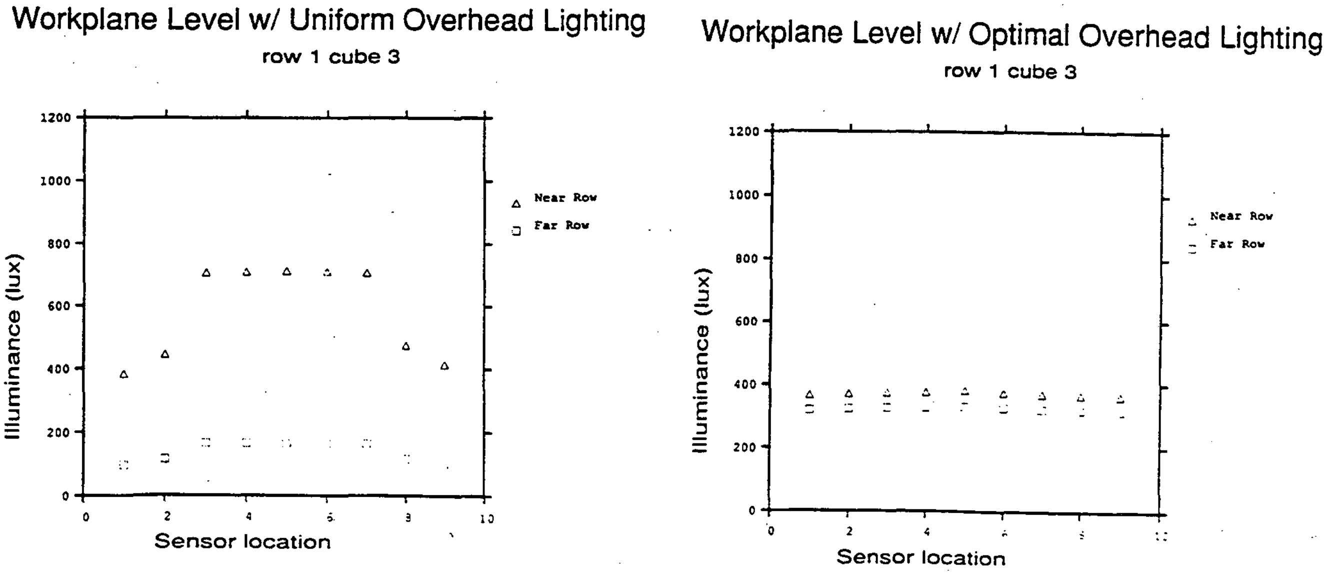

Figure 4. Desk illumination for original and optimized overhead lighting.

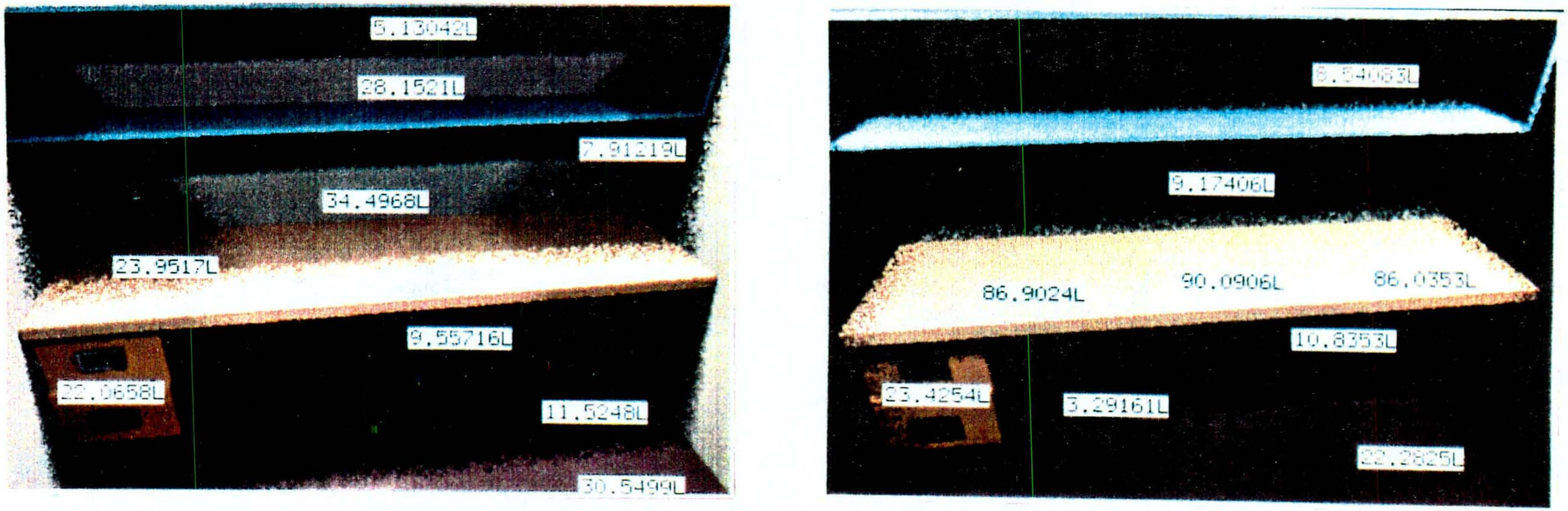

Figure 5. Vacant desk under original and optimized overhead lighting. Luminance values are in candelas/square meter.

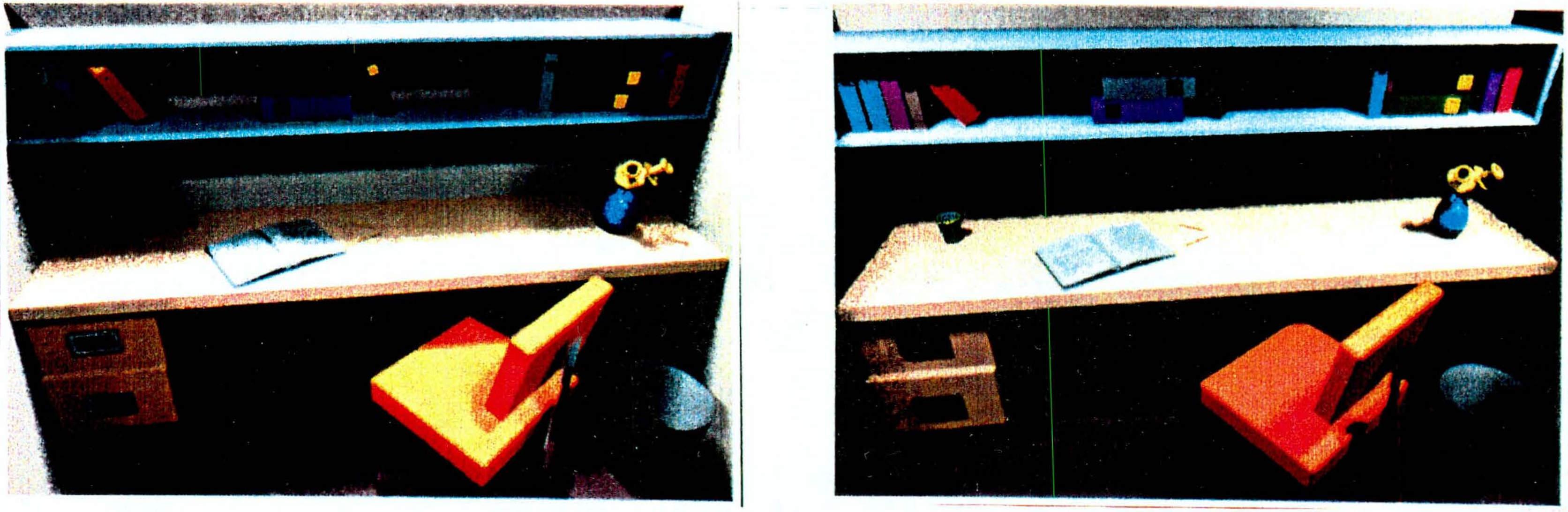

Figure 6. Furnished desk under original and optimized overhead lighting.

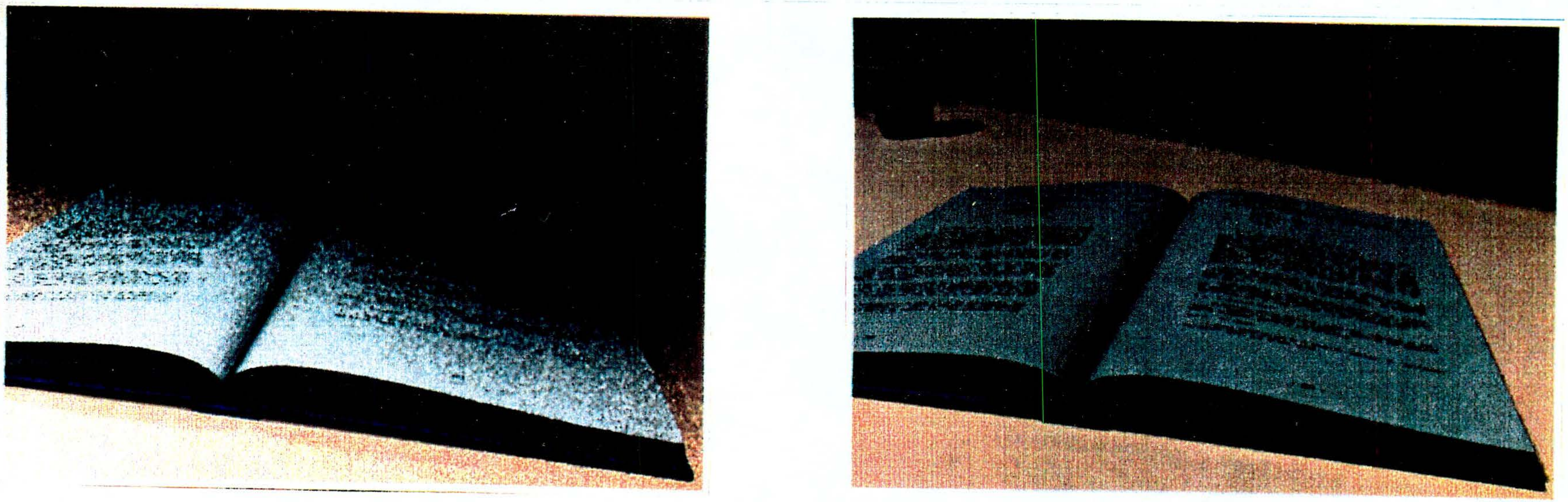

Figure 7. Reading task under original and optimized overhead lighting.

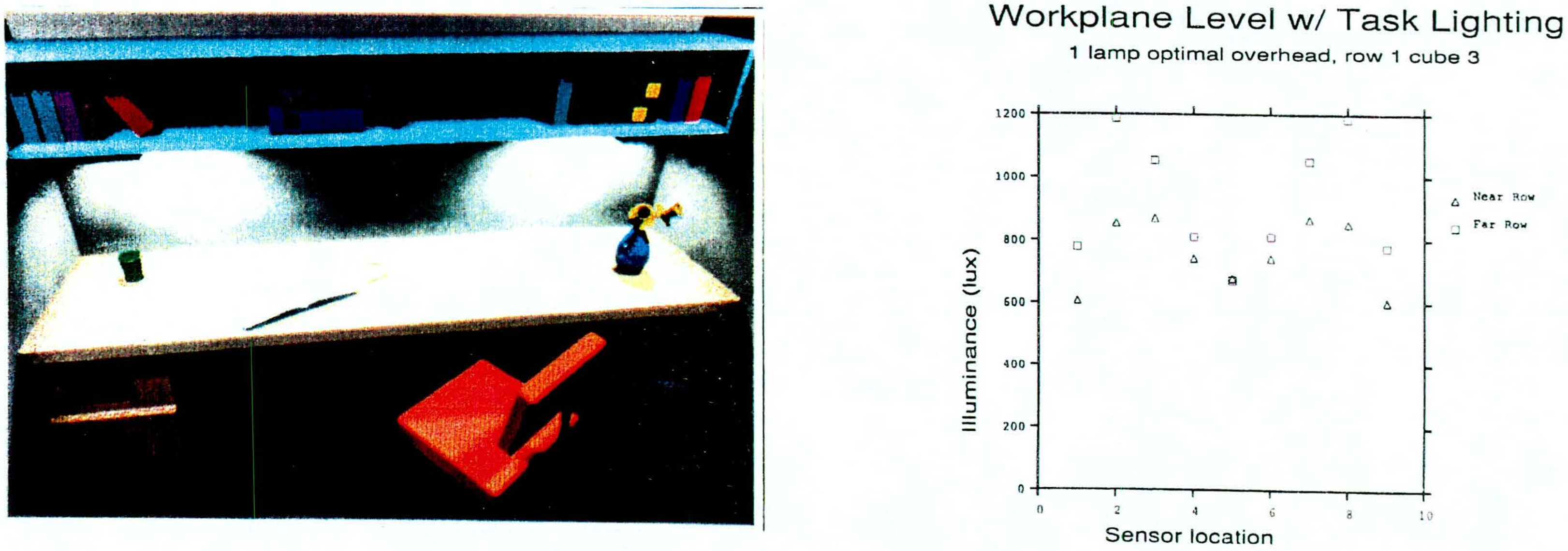

Figure 8. Desk illumination with task lighting added to optimized overhead layout.

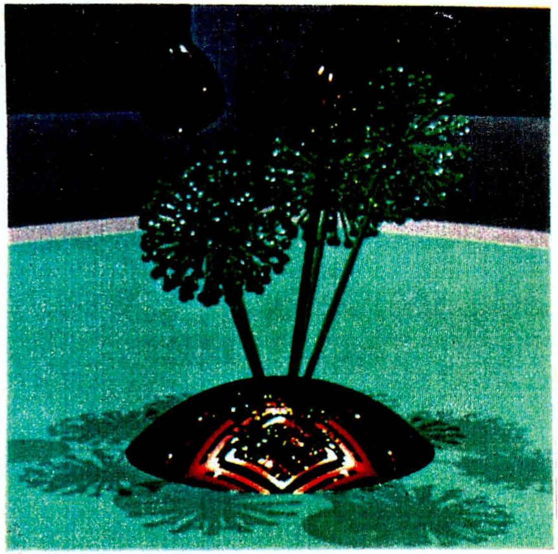

Figure 9. Sculpture under general area lighting.

Figure 10. Sculpture with two overhead floodlights.

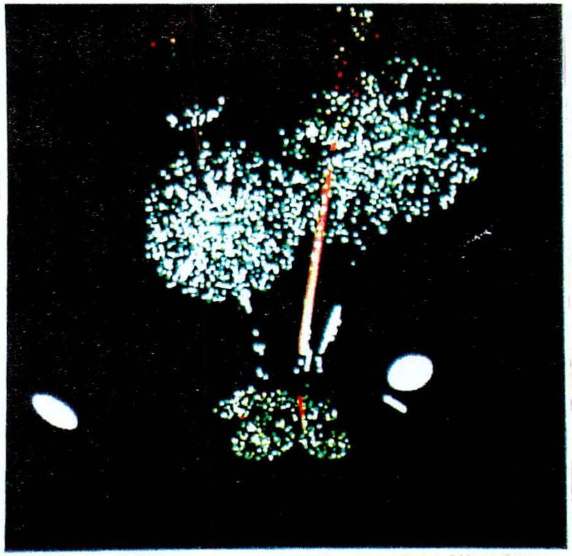

Figure 11. Sculpture with three floodlights at base.

Figure 12. Combination of general and overhead lighting.

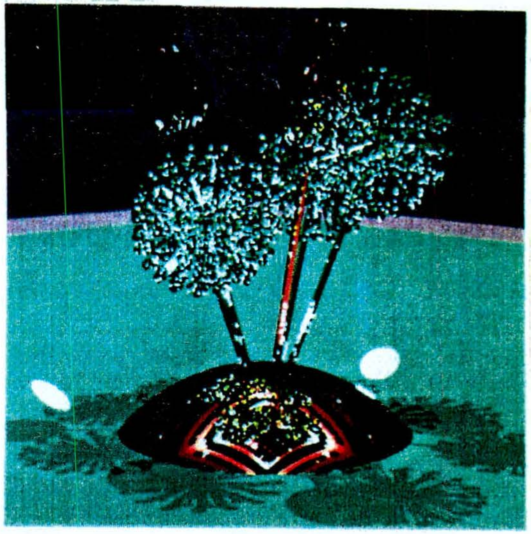

Figure 13. Combination of general and base lighting.

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