Validation of the *pcond* Visibility Matching Tone Mapping Operator

Comparing Subjective Responses to Computer Simulated Images and Scale-model Environments

A Masters Thesis Proposal

A. PROJECT SUMMARY

Human subject studies are performed to validate and refine the general-purpose luminance to brightness (tone) mapping algorithm of a software program called *pcond*. Through survey questionnaires, subjects compare a rendered image displayed on a video monitor with a scale-model representation of an identical space incorporating the full dynamic range of the luminous environment typical of office spaces. A validated tone mapping operator enhances the reliability and repeatability of computer-based simulation and visualization technologies thereby improving the building industry's ability to predict the visual impact of proposed architectural projects. Applications relevant to this study range from daylighting in office environments to nighttime lighting of bridges and building facades. Secondary applications include height dynamic range photography, video game design, and general-purpose renderings for animations, film, and movie production.

C. PROJECT DESCRIPTION

C.1. INTRODUCTION

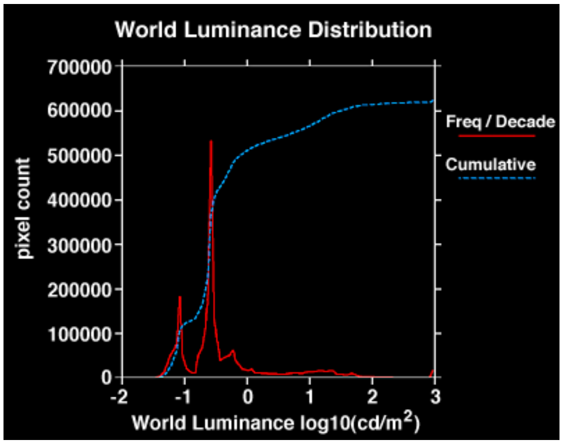
Architects rely upon accurate simulations to understand the impact of proposed buildings. Architects are also responsible for presenting an honest representation of a proposed building to a prospective client. Architecture firms are finding the use of three dimensional computer aided design tools to be essential both for in-house design analysis and for preparing high profile presentations. Yet clients are not asking the question, "Is this what my building will actually look like?" Such a question can relate to both the intangible qualities of a building that are conveyed through the design intent or parti as well as the quantitative information about light levels and visibility conditions that affect occupant health, comfort and productivity. Architectural firms find it necessary to insert imaginary light sources into their models to achieve “realistic” lighting simulations. Indescriminating building owners seem to be satisfied with "artist's renditions" and otherwise plastic and highly abstract representations of what the building’s designers *expect* the building to look like. Architects prefer the abstract representation of artist’s renderings because it allows them to easily change their mind. But this privilege is easily abused and can lead to buildings that do not meet design specifications. These issues and the potential damage cuased by not appropriately addressing them are crucial when evaluating projects that utilize daylighting. Buildings such as the High Museum in Atlanta are unable to accept many travelling exhibits because it admits too much daylight. The High Museum and other buildings (there are many) would have benefited from a predictive tool that can reliably simulate the lighting and visibility conditions in the proposed building before it is built.

Such a system now exists, but heretofore has been inaccessible because of a very difficult, unfriendly user interface. The *Radiance Lighting Simulation and Rendering System*[1] is highly respected[2] for its architectural visualization capabilities due to its renowned accuracy and its validated, physically-based rendering system. Lawrence Berkeley National Laboratory is currently funded by Pacific Gas and Electric Company (through the California Board for Energy Efficiency) to develop a CAD-based user interface for *Radiance*. But a significant limitation to the widespread use of *Radiance* still exists. The new method through which the images produced by *Radiance* are displayed on the computer monitor has yet to be rigorously validated. Until such a validation has been performed, little confidence in the displayed images can be presumed.

A physically-based simulation algorithm such as *Radiance* is essential to evaluate the visual environment of daylit architectural spaces. Individuals and institutions around the world have performed numerous validation studies[3] of the underlying algorithms of *Radiance*. But only recently has the author of *Radiance* provided a systematic way of displaying the images on a computer monitor in a manner he claims to closely represent how a human would visually perceive the depicted space.[4, 5] Other validation of ***pcond*** include a study by NASA focused on how the low light level loss of acquity is simulated. The focus of this proposed research is validation of the display technology of *Radiance* called ***pcond*** and not the underlying ray-tracing based rendering algorithms of *Radiance*.

C.2 BACKGROUND

The ***pcond*** display method employed by *Radiance* is primarily based upon human subject studies performed by Stevens and Stevens[6] in the 1960's and on Moon and Spencer[7] in the 1940's. At illuminance levels typical of office environments,[8] the ***pcond*** display method calculates a photopically-weighted exposure response curve, called a tone mapping operator, based upon the range of luminances within the field of view. The values of all input pixels in the simulated image are sorted by frequency of occurrence creating a histogram of luminance values. (See figure 1). The tone mapping operator optimizes the computer display output brightness levels by employing the knowledge that human vision is globally (within the total field of view) insensitive but locally (within the peri-fovea) very sensitive to luminance differences. (See figure XXX). Where the histogram of pixel luminance shows a large concentration of values, the corresponding range of output brightness levels is expanded (the slope is increased). Where the histogram contains few luminance values, the output brightness range is compressed (the slope is decreased). (See figure 2). Because it is possible to produce computer-adjusted images which are super-realistic (showing more tonal separation than the eye is actually able to resolve), the tone mapping curve between these regions is clamped to no greater than a linear relationship (slope ≤ 1). (See figure 3). The tone mapping operator thus derived adjusts the exposure of each pixel to arrive at a human sensitivity adjusted image of the architectural space.



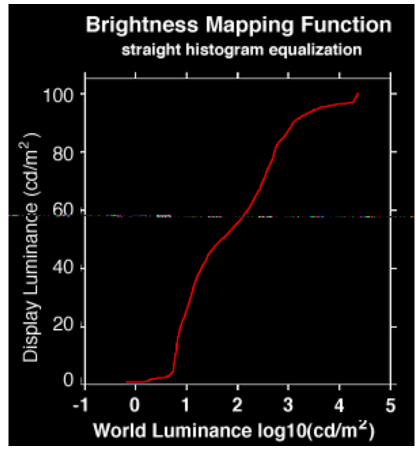


Figure 1 (left) and figure 2 (right)

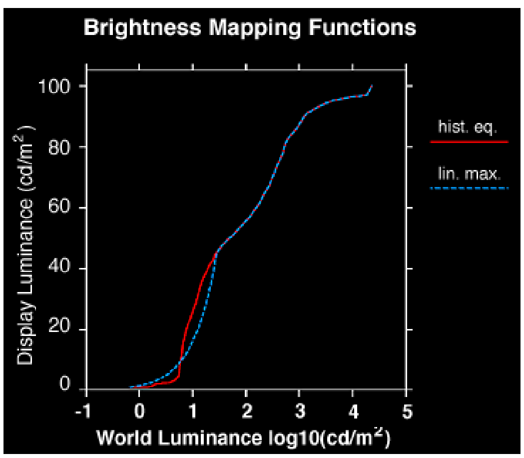


Figure 3 (left) and the subject image figure 4 before (middle) and figure 5 after (right)

How closely does this display method match subjects' responses to the actual space? The ideal computer display would exposed the viewer's retina to the same physical stimulus as the built space over the full 10,000 to 1 dynamic range, however, this is not possible with today's computer display technology. The next best condition would be if the viewer exhibited physiological responses to the images identical to the view of the built space. Is it possible to approximate physiological responses to an environment of 10,000 to one luminance ratios on a computer display capable of only 100 to one ratios? Since the physiological response will not be identical, will subjects extrapolate "feelings" which are similar to the most likely physiological response to the built space? What is the reliability and accuracy of a display technology that aims to provide hints about the subjective response of a built space with an accurate simulation viewed on a low dynamic range display device?

Based upon my experience of a variety of images produced with *Radiance* and displayed with this new tone mapping technology, the method is a vast improvement over the previous method. The previous method used a simple linear mapping of image luminance to display brightness based upon an average exposure value. Luminances beyond the dynamic range of the output device were clamped to the minimum or maximum brightness of the device, i.e., black or white. This often resulted in images that appeared too bright, too dim, or unrealistic. In fact, it was difficult to determine the most appropriate exposure level for the image leaving this final, crucial step open to wide interpretation and human error. It was possible to display images that conveyed vastly different impressions of the space depending upon the selected exposure value. The new method, however, consistently delivers appropriately exposed images and displays images that very closely resemble the built space.

C.3 OBJECTIVES

This research project will investigate the claim that *Radiance* images adjusted with Greg Ward-Larson's tone mapping operator, ***pcond***, elicit accurate subjective responses to daylit office environments. Milestones include the fabrication of scale models with a high dynamic range of brightness values, modeling and rendering matching scenes with *Radiance*, creation of the experimental comparison chambers, assembly of the computer display devices, developing the survey questionnaire, and initial testing of the entire experimental apparatus with volunteer subjects drawn from the UC Berkeley campus. If adequate funding levels are achieved, then the survey sample size will be increased and diversified with paid subjects of various ages, and ethnic and socio-economic backgrounds.

C.4 METHODS

Two primary methods can be employed to test this hypothesis: in-situ experiments of actual office environments or ex-situ comparisons of highly controlled model environments containing known ranges of brightnesses. The second method was employed by Osterhaus to develop a glare index for large area sources[9]. The first method captures the effect of the spectral content of daylight on the subject, but suffers from an inability to isolate environmental influences from the experimental apparatus. Any method of evaluating subjective responses to simulated versus physical environments also needs to remove the subjects' awareness of the operative variable (whether computer or physically based rendering). Scale models provide much greater control of both of these parameters.

The main body of work for this research involves the construction of an experimental chamber and its accompanying scale models and corresponding computer 3D models. The chamber provides a series of monocular view ports which place the subject's eye at a precise location relative to the experimental variable: either a computer display or a scale model of a typical daylit office environment. The lighting levels in the chamber will be controlled precisely so that the adaptation level of the subjects is also known. The level of detail in the simulated space and the scale model is matched and the perspective distortion of the model and simulated views are identical. The computer display is of high enough resolution and located far enough away from the view portal to prevent the perception of individual computer pixels. The objective is to provide the fewest possible clues that the view is either computer generated or a scale model. Between tests, the viewing apertures for one side of the experimental apparatus are obscured while the scale models and computer displays are randomly rearranged.

The subject will be asked to find the two views that are most similar to each other indicating the degree of similarity on the survey form. Various parameters of the display algorithm will be adjusted and compared with two versions of the scale model. One of the physical models will simulate a sky with electric lights sufficient to reproduce the high dynamic range of luminances experienced in the real world (10,000:1). The other physical model will simulate a sky with low dynamic range typical of what can be reproduced on a computer display (100:1).

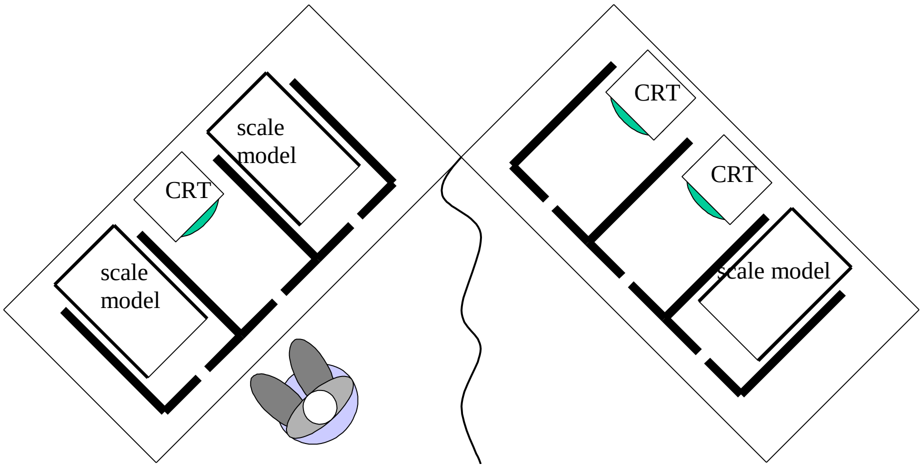


Figure 6 Diagram of the experimental apparatus showing scale models and CRT displays.

If initial results show that pcond does not reproduce a matching response, the parameters of the tone mapping operator will be adjusted. Perhaps a linear clamping of luminance to brightness is not appropriate or perhaps the slope of the clamping varies with luminance or with the degree of separation between the neighboring luminance concentrations.

C.5 SIGNIFICANCE

This research will bring us closer to a validated method for predicting and visualizing the impact of visual phenomenon with a large dynamic range of luminances within the field of view particularly those found in daylit architectural spaces. With a validated model for understanding daylighting, building designers can more confidently accept the simulated images as an accurate and reliable representation of proposed architectural projects. With greater confidence that daylighting designs will not be harmful to the performance of the building or its occupants, designers are more likely to implement daylighting strategies. ***Pcond*** will be incorporated into another software currently in development at Lawrence Berkeley National Laboratory called *Desktop Radiance*. Together these software make it easier for architects to design buildings that are more energy efficient with the use of daylighting technologies. While little support for such claims exists, it is not possible to verify their veracity until a validated simulation and display method exists. This research will provide this missing link.

The ***pcond*** tone-mapping operator has many potential applications besides typical RGB color monitors including head-mounted displays, immersive "VR" displays, "caves" and high dynamic range photography[10]. The results of this research will be submitted for publication in the SIGGRAPH and IESNA journals. If improvements to the underlying algorithm are implemented, this modified code will be made available to the world at no cost through the *Radiance* web site.

E. BIOGRAPHICAL SKETCHES

PRINCIPAL INVESTIGATOR

Charles Ehrlich has spent over 10 years working with *Radiance* in various capacities. He currently works half time at Lawrence Berkeley National Laboratory for the Building Technologies Program while attending graduate school. In 1990, he established a private consulting practice focused on the use of *Radiance* for lighting analysis. His clients have included architects Mark Mack, Polsheck and Partners, Skidmore, Oewings and Merril, and Cesar Pelli and Associates, Horton Lees Lighting Design of New York, Energy Simulation Specialists of Tempe, Arizona, Cunningham and Associates of San Francisco, Stephen Winter and Associates of Norwalk, Connecticut, and attorney Alan Moss of San Francisco. Space & Light has completed projects including the daylighting of the Inventure Museum in Acron, Ohio, exterior lighting of a skyscraper Bank Headquarters in Winston-Salem, North Carolina, a theater in San Francisco, the new International Lobby building at the San Francisco International Airport, a terminal building interior at the Ben Gurion International Airport, a library, a utilility headquarters building, daylighting analysis for Wall Mart stores, and several legal cases including one train-pedestrian accident. Charles Ehrlich earned his Bachelors of Architecture degree from the University of California at Berkeley, College of Environmental Design in 1989 and has returned to his alma mater to earn his Masters of Science degree in Architecture. Current coursework includes the methods of architectural research, an architectural field methods course, and a programming course. Next semester will include a course on the psychophysics of the human eye, a software interface design course, and a course on the advanced study of energy issues in architecture.

PROJECT ADVISORS

Professor Cris Benton of the College of Environmental Design is the primary advisor.

Greg Ward-Larson of Silicon Graphics will advise on software implementation issues.

Professor Theodore Cohn of the U.C. Berkeley School of Optometry will advise on vision related issues.

D. REFERENCES

[1] Ward, G. 1994. The Radiance Lighting Simulation and Rendering System, *Computer Graphics Proceedings Annual Conference Series* 459-472. http://radsite.lbl.gov/radiance

[2] During the ACM/SIGGRAPH98 conference (a technical forum for computer graphics research), six papers were presented that featured *Radiance* in some capacity, either as the main topic of the paper, as the base algorithm upon which additional research was based, as the rendering "engine" used for a particularly innovative animation, or as the "baseline" upon which a new algorithm was compared for accuracy purposes. During an exhibit of *Radiance* software at the 1997 Annual Conference of the Illuminating engineering society of North America (a technical forum for architectural lighting research), I conducted an informal survey of attendees who visited our booth. Ninety percent of all respondents were familiar with the name *Radiance* and associated it with "an accurate simulation tool."

[3] Several validation studies of *Radiance* have been conducted and can be found at: http://radsite.lbl.gov/radiance/papers

[4] Ward, G.J. 1997. A Visibility Matching Tone Reproduction Operator for High Dynamic Range Scenes. LBNL Report 39882. Lawrence Berkeley National Laboratory. http://radsite.lbl.gov/radiance/papers/lbnl39882/tonemap.pdf. From the manual for ***pcond*** "-h[+-] Mimic human visual response in the output. The goal of this process is to produce output that correlates strongly with a person's subjective impression of a scene." The manual can be found at http://radsite.lbl.gov/radiance/man_html/pcond.1.html

[5] A quick overview of the method can be found at: http://www.sgi.com/Technology/pixformat/files/sg97sketch.pdf

[6] S. S. Stevens and J.C. Stevens. 1960. "Brightness Function: Parametric Effects of adaptation and contrast," Journal of the Optical Society of America, 53, 1139.

[7] P. Moon and D. Spencer. 1945. "The Visual Effect of Non-Uniform Surrounds", Journal of the Optical Society of America, vol. 35, No. 3, pp. 233-248

[8] At low light levels, loss of color contrast and acquity is also accounted for in the ***pcond*** display algorithm.

[9] Conversation with the author.

[10] A description of Greg Ward-Larson's continued work on ***pcond*** for photographic reproduction at Silicon Graphics is described at: http://www.sgi.com/Technology/pixformat/tiffluv.html