The 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST (2005)
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Short Presentations

Towards Image-Based Measurement of Perceived Lightness applied to Paintings Lighting.

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Abstract

A relevant problem in the evaluation of illumination conditions on ancient paintings and frescos is the needing of some kind of measure of the perceived light not only from a metrological point of view, but also considering the visual perception of the observers. In this paper, we propose a comparison between different lightness definitions applied to lighting measurements acquired by Imaging Luminance Measurement Device (ILMD) on paintings illuminated by daylight, in order to setup a more comprehensive system to evaluate the effective quality of the illumination of museums and art galleries. We actually considered some well-known lightness definitions working on the global image, but we want to investigate local adaptation algorithms.

Categories and Subject Descriptors (according to ACM CCS): I.4.8 [Image Processing and Computer Vision]: Scene Analysis

1. Introduction

One of the main problem in the observation of ancient paintings and frescos is due to the degradation of colors pigments and to the deposition of dirt, that make them appear darker. These phenomena cause also a degradation in the contrast of visible colors. If on one side experts in restoration can try to limit the damages occured in the years, on the other side the responsibles of the management of the art works should care, for the appreciation of a wide audience, about projects of the exhibitions that take in high consideration lighting design and visual perception. Unfortunately, in many cases, the project of the exhibitions is done ignoring some of the principal behaviors of visual perception and of safeguard of pigments from light. Some of the mistakes that may be observed in museums are, for example, to place a painting darkened and faded from time consumption over a white background wall and over-illuminate it, or to leave it under direct or indirect daylight: that is, the absence of a correct design of perception and illumination.
The starting point of our research is the idea to supply methods and scientific instruments useful to evaluate not only the illuminance of ancient paintings and frescos, but also the perception, from a quantitative (i.e. metrological) point of view. The goal is to supply precise and measurable data, not only on the illuminance and luminance, but also on the quality of the perception of the works in terms of contrasts and of direct and indirect glares, considering the real mechanisms of visual perception of light.

2. Image-based Measures

In Photometry, the measure of the amount of luminous flux that can reach the human eye is the luminance L. The luminance of a surface A is given from the ratio between the luminous intensity I outgoing the surface and his apparent area $L = dI/(dAcos(\theta))$, where θ is the angle of inclination between the surface and the viewing direction. The instruments used to measure luminance are called luminance meters [CIE87b] and their measure unit is cd/m^2. Recently, ILMD (Imaging Luminance Measurement Devices, also known as video-photometers or CCD luminance-meters) [Bla05] have

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been introduced and a new CIE Commission, called "TC2-59 Characterisation of ILMD", has been established. An ILMD can measure luminance of a real scene giving as results an image with a colors or grey-levels map of the measured values (see Fig. 1 for an example).
ILMD are very interesting instrument for a lighting designer: they allow us to quickly measure uniformity values, contrasts and spatial distribution of luminances of a lighting system. The idea of using image analysis in the evaluation of interior lighting has been confirmed in the last years in many research projects [VFA91] [BF95], and actually it has found new resources from CCD usage in luminance measurements [KIK97] [BF98] [BCMS99]. ILMD are based on CCD (Charge-Coupled Device) sensors, similar to those used in digital photos. The measured irradiance value in each single cell in the CCD is converted in a digital value. Regarding measurement accuracy, video-photometers can have different kinds of CCD, from 16 to 8 bit. In the first case the device can acquire 65.536 different levels of luminance; many researches have addressed the problem of the calibration of these devices [BCMS99] [Int99] [FIMR03] [BCM*03]. Some kind of ILMD, having a low-dynamic CCD, are based on an automatic mechanism that acquires a sequence of images at increasing exposure intervals, so to capture a larger range of luminance values [DM97].
Many research projects have addressed the cromaticity measure of pigments in ancient paintings [VCC94] [MSC*96] [SNP04] [AFOR04] using CCD with non-invasive methods. Other works have been mainly dedicated to the implementation of instruments useful in the colors choice for the restoration or the archiving of paintings [AFOR00] [Ber01] [NPS05] [TMT01]. Recently, regarding restoration settings, it has been comprised the importance of the spectral characteristics of lighting in the relation between restoration and exposition stages [SRC05].

3. Perceptual evaluation of surfaces luminance: lightness

ILMD can give us a recontruction of the luminance values in a scene; however, the human visual system does not operate as a measurement device. In fact we have remarkable abilities to adapt to changes in luminance until 7 orders of magnitude. From a perceptual point of view we talk about *brightness* in case of surfaces emitting light, and we talk about *lightness* in case of surfaces refletting light [CIE87a]. Our interest for *lightness* is due to our intent to measure real vision of art works in function of the perceptual adaptation of human visual system.
Relation between luminance and brightness/lightness is a research topic addressed in all the world. Since the researches from Stevens [SS60], several definitions of lightness have been proposed [CIE88] [CIE95] [WS82]. In the following subsections we will describe briefly some of the most known and used lightness measure. Then we will discuss the problem of their application on ILMD data and also we will introduce some ideas about the future implementation of a new measure with the aim to obtain a correct perceptual evaluation of lighting on ancient paintings.

3.1. CIE Luminance Factor Y

Most of the measures proposed in the years are based on the CIE Luminance Factor Y. It is defined as:

$$Y = K' \int_{\lambda=380}^{780} S_e(\lambda) R(\lambda) \bar{y}(\lambda) d\lambda \qquad (1)$$

where $S_e(\lambda)$ is the Relative Spectral Radiant Power Distribution of the illuminant and $R(\lambda)$ is the Spectral Reflectance Factor of the surface. The normalization constant K' is defined as:

$$K' = \frac{100}{\int_{\lambda=380}^{780} S_e(\lambda) \bar{y}(\lambda) d\lambda} \qquad (2)$$

From formulas 1 and 2, Y may have a value from 0 to 100. Y can have the maximum value of 100 only in the case of the ideal diffuse reflector (for which $R(\lambda) = 1$).

3.2. CIE Lightness Index W^*

The CIE Lightness Index W^* was proposed as lightness measure in the CIE UCS 1964 uniform color space [CIE63]. The formula for W^* is:

$$W^* = 25 \cdot \sqrt[3]{Y} - 17 \qquad (3)$$

where Y is the CIE Luminance Factor defined in formula 1. W^* may have negative values: in fact its range of values is from -17 to 100. In 1976, it has been replaced by the CIE Relative Lightness L^*.

3.3. CIE Relative Lightness L^*

The CIE Relative Lightness L^* was introduced as lightness measure in the CIELUV and CIELAB color spaces [CIE04]. These spaces try, even if in a partial way, to consider some complex vision mechanisms, as the cromatic adaptation to the illumination. The formula for L^* is:

$$L^* = \begin{cases} 116 \cdot \sqrt[3]{Y/Y_n} - 16 & \text{if } (Y/Y_n) > 0.008856 \\ 903.3 \cdot (Y/Y_n) & \text{if } (Y/Y_n) \leq 0.008856 \end{cases} \qquad (4)$$

where Y is the CIE Luminance Factor defined in formula 1 and Y_n is the luminance factor of the ideal diffuse white reflectance sample (usually, $Y_n = 100$).
L^* can assume values from 0 to 100.

3.4. Munsell Value V

The Munsell Value V [WS82] is defined in the Munsell Renotation Color System, that is accepted by many standards and professional organizations concerned with color samples. The system describes color using three variables: Hue, Saturation, and Value. In the three dimensional space defined by this system, the central axis represents Value, hues are organized around the axis, and saturation increases away from the axis. The relation between Munsell Value V and CIE Luminance Factor Y is reported in the following formula:

$$Y = 1,2219 \cdot V - 0,23111 \cdot V^2 + 0,23951 \cdot V^3 + - 0,021009 \cdot V^4 + 0,0008404 \cdot V^5 \quad (5)$$

Also, in 1974 CIE has established a very simple relation between the Munsell Value and the CIE Relative Lightness L^* [CIE74]:

$$V = \frac{L^*}{10} \quad (6)$$

It is straightforward from formula 6 that the Munsell Value V can assume values from 0 to 10.

3.5. DIN Darkness Degree D

DIN Darkness Degree D is defined in DIN 6164 Color System [DIN80], a color space developed in Germany and largely diffused in Central Europe. It uses CIE standard illuminant C as the achromatic color stimulus. The lightness measure defined in this color space is defined in the following formula:

$$D = 10 - 6.1723 \cdot \log_{10}(40,7 \cdot h + 1) \quad (7)$$

where:

$$h = Y/Y_0$$

The factor h is defined by the ratio between CIE Luminance Factor Y of the surface and the luminance factor Y_0 of the optimal color stimulus having the same chromaticity as the surface.

3.6. OSA Color System lightness L

The OSA Color System was developed between the years 1945 and 1974 by the Optical Society of America [Mac74]. The lightness measure introduced in this system is given by the formula:

$$L = 5,9 \cdot \left(\sqrt[3]{\overline{Y}_{10}} - 2/3 + 0,042 \cdot \sqrt[3]{\overline{Y}_{10} - 30} \right) \quad (8)$$

where the luminance factor $\overline{Y}_{10}$ is defined as a function of Y_{10}, x_{10} and y_{10}, i.e. the CIE 1964 color specification of the stimulus:

$$\overline{Y}_{10} = Y_{10} \cdot (4,4934x_{10}^2 + 4,3034y_{10}^2 - 4,276x_{10}y_{10} + - 1,3744x_{10} - 2,5643y_{10} + 1,8103)$$

The value of $\overline{Y}_{10}$ is 100 for the ideal reflector under CIE standard illuminant D65.

3.7. CIECAM02 lightness J

The CIECAM02 color appereance model [MFH*02] was proposed in 2002 as an evolution of the former CIECAM97s model. It has relevant components of locality in the determination of color and of other factors: it is considered, for example, the influence of the background color and of the surround, the adapting stimulus and also the degree of adaptation. It is not our intention to give a full description of CIECAM02 model: so we just focused here on the lightness measure formulas. For a complete description, we remand to CIE TC 8-01 website [TC8].
The lightness J of CIECAM02 model is given by:

$$J = 100 \cdot (A/A_w)^{cz} \quad (9)$$

where the factor A (the acromatic rensponse for the stimulus) is calculated by the formula:

$$A = [2R'_a + G'_a + (1/20)B'_a - 0,305] \cdot N_{bb} \quad (10)$$

In formula 10:

- N_{bb} is the brightness background factor, that is a function of a background induction factor (called n);
- R'_a, G'_a and B'_a are the adapted cone responses, generated using a function of a luminance level adaptation factor, and of a triplet R', G' and B', calculated by a Chromatic Adaptation Transform (CAT02) on the original XYZ values of the stimulus. CAT02 is based mainly on a von Kries normalization.

In formula 9:

- A_w is the achromatic response for the white point, and it is determined as in formula 10, but applied to R'_w, G'_w and B'_w (the adapted cone responses for the white point);
- c is the impact of the surround parameter;
- z is the base exponential nonlinearity factor, that is a function of the background induction factor n (as N_{bb} parameter in formula 10).

4. From global to local measurement

All the lightnesses exposed in the previous subsections were implemented on the basis of the well-known Weber's law, that describes the relation between a stimulus and its perception: so, all the formulas proposed have as main function a logarithm or a cubic root. The difference between them is the argument of this function, i.e. what is explicitely addressed in some formulas as "luminance factor". It is straightforward, as a first step in our research for a new perceptually correct measure, to look at the nature of these parameters, with the aim to evaluate their applicability to the measured values from ILMD.
It's evident how lightnesses that are expressed not only in terms of the luminance information, but that use also the chromatic information, can not be directly considered and applicated: in fact ILMD usually are constructed with the

Figure 1: *ILMD output grey-levels map of the GiamBattista Tiepolo's painting "Madonna of Mount Carmel and The Souls in Purgatory", Brera Art Gallery, Milan.*

Figure 2: *Grey-levels map of lightness values generated from data shown in Figure 1 using CIE L^*. The luminance factor in each pixel is given by the ratio between the luminance value and the maximum value of luminance in the scene.*

intent to acquire or to recontruct only the luminance values for each point, without considering chromaticity. Obviously, this restriction can be eliminated if in the future ILMD standard specifications will be considered a correct reconstruction of chromatic values. However the odiern situation tells us that a lightness measure for ILMD may be implemented only considering luminance values. The lightness measures that use chromaticity information are the DIN Darkness Degree D (formula 7), the OSA Color System lightness L (formula 8) and the CIECAM02 lightness J (formula 9).

On the other side, also the remaining measures, i.e. CIE Lightness Index W^* (formula 3), CIE Relative Lightness L^* (formula 4) and Munsell Value V (formula 5), are not directly applicable to ILMD measured data. In fact they are expressed in terms of the CIE Luminance Factor Y, that is based (formula 1) on the adimensional Relative Spectral Radiant Power Distribution $S_e(\lambda)$ of the illuminant. However, the luminance acquired by an ILMD is photomtrically defined by the following formula:

$$L = 683,0 \int_{\lambda=380}^{780} L_e(\lambda)\bar{y}(\lambda)d\lambda \qquad (11)$$

where $L_e(\lambda)$ is a physically measurable Radiance Spectral Distribution. Trying to put in relation the adimensional $S_e(\lambda)$ with $L_e(\lambda)$ is a non-trivial task without a measure of the spectral distribution of the acquired luminance. A pratical solution is to change the definition of the luminance factor applied in the lightness measures, basing it only on the available data, i.e. the luminance values for each pixel: in Figure 2, for example, is shown a grey-levels map of lightness values generated from the ILMD measured data of Figure 1 using CIE Relative Lightness L^*. The luminance factor in each pixel is the ratio between the luminance value and the maximum value of luminance in the scene.

The major point that we want to address in this preliminar study is the importance of *locality* in the final perceived lightness. Normally, some kind of ideal diffuse white reflectance sample is defined under a particular standard illuminant, and the lightness is calculated in a uniform way for all the acquired image, not considering other information from the scene. On the contrary, it is largely demonstrated that our visual perception has strong local characteristics [Mar82]. The perception in a point is affected by its surround, by the distribution of luminance values in the observed scene, and also the area of the surfaces on which the stimulus is measured have a relevant importance.

In our opinion, a correct measure for perceived lightness applied to lighting measurements acquired by ILMD must be a local, image-based formula, based only on the luminance values measured, and that considers effective mechanisms of visual perception: no arbitrary ideal diffuse white reflectance sample must be defined, but we suggest to pick the maximum value of luminance in the scene as the reference for the determination of the luminance factor to be processed in the new formula. Moreover, to introduce locality in the determination of the luminance factor, weight parameters must be added, based on spatial relations between the stimulus and the maximum luminance: distance, relative position in the scene, visual field, are some of the factors that may be included in the new model. In fact, two points in an image with same luminance value measured by an ILMD, have different perceived lightnesses, if one of them is near the point with maximum luminance value, and the other is at the border of the visual field. Another factor relevant in the correct determination of lightness may be the size of subsets of contiguos pixels in the image having nearly the same luminance values, and their relation in the determination of the luminance factor.

5. Conclusions

In this paper we have introduced the problem of the evaluation of a perceptual measure of lightness from the luminance values acquired by ILMD on ancient paintings and frescos. We have exposed our opinions on some well-known lightness measures defined in literature and included in standardized color systems, in terms of their application to the luminance values acquired by actual devices, and we have preliminarly discussed some points about the implementation of a new lightness measure with the aim to obtain a correct perceptual evaluation of illumination on ancient art works. We resume the principal keypoints of the new measure:

- it must be based only on luminance information;
- it must be a local, image-based method;
- luminance factor must be based on the relation with the maximum luminance value in the scene and not on arbitrary ideal diffuse white reflectance sample;
- it must be based on many "geometric" parameters: e.g. distance from maximum luminance value, relative position, visual field.

The implementation and validation of this new measure will be exposed in future publications.

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