# Extreme Spectral Power Distribution of Light Source and its Impact to Vision and Cameras Sensitivity

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## Abstract

*Thanks to the advancement of technologies, we may be having more flexibility to determine the spectral power distribution (SPD) of light sources. Suppose any SPD is possible, we derive "extreme SPD of light source" aiming at a specific purpose such as the lowest energy, the largest color gamut, the lowest impact to fine arts, etc. We found that these SPDs always consist of multiple spikes when very high CRI is not required while the SPD of the black body radiation is continuous in wavelength. In order to investigate the effect of such light sources to human visual system and camera system, we employ two types of such light sources, namely Maximum White Luminous Efficacy of Radiation (MWLER), which gives the best energy efficiency, and Maximum Gamut Area (MGA), which gives the largest color gamut size. Both MWLER and MGA are composed of multiple spikes in wavelength. We generate such SPDs with respect to 6 types of existing light sources with same CCT and CRI (if applicable), and evaluate how sensitive these are with 10 sets of color matching functions (CMFs) given by Stiles and Burch as human visual system and 4 sets of digital camera sensitivities by computer simulation. We presume a color matrix of color conversion for CMFs and camera is adjusted minimizing errors with a Macbeth Color Checker under black body radiation with the white point constraint. With this assumption, we evaluate colorimetric error under the two extreme SPDs in addition to black body radiation and existing light sources. We find that cameras give large error (more than 20 in $\Delta E^*_{ab}$) for these spiky light sources which may not be accepted by users even when they are in a tolerable error range for the human visual system. It is concluded that such spiky light source could be used without problem for a variation of CMFs, but it would be problematic for color reproduction of cameras.*


## Introduction

The energy consumption of lighting system is a major concern in today's society. Governments encourage developing more efficient light sources and smart controls. There are basically three approaches to improving lighting efficiency: (1) improvement of quantum efficiency, (2) optimization of SPD, and (3) smart and adaptive control. The first one requires improving materials and structure of devices. The second one requires designing spectral distribution satisfying color quality and luminous efficacy. The third one requires designing the light management system with sophisticated sensors and algorithm to control the intensity of lights depending on ambient light, occupancy and usage. In this paper, we focus on SPD described in (2).

It is well known that Luminous Efficacy of Radiation (LER) will be affected by Color Rendering Index (CRI) and Correlated Color Temperature (CCT). We have shown the theoretical limit of LER and have proposed the concept of MWLER [1], namely MWLER light. It becomes a combination of spike-shaped spectral distribution if CRI is not extremely high. We suggest that it be used as the target of energy-saving light design; i.e. MWLER ratio, which is the LER ratio between testing light and optimum spectral light source having the same CRI and CCT on the Planckian locus. We demonstrate that most of lights used in the market have potential to be improved in terms of LER by 20-30% without sacrificing efficiency and color quality. An example is shown in Figure 1.

As an extension of the idea, when the SPD of light source is optimized for a certain purpose, it is predicted that the SPDs of such light sources tend to be spiky. For example, in some cases, it is composed of three-to-five spikes of monochromatic lights. It was intuitively imagined that such a spiky SPD might be very sensitive to individual variations of eye sensitivity and camera sensitivity while a continuous SPD would not be sensitive for them.

In this report, firstly, we demonstrate some examples of extreme light sources composed of spiky SPD. Secondly, in order to quantitatively evaluate the vulnerability for visual system and camera system, we evaluate color errors to confirm the robustness of such spiky light sources by simulation.

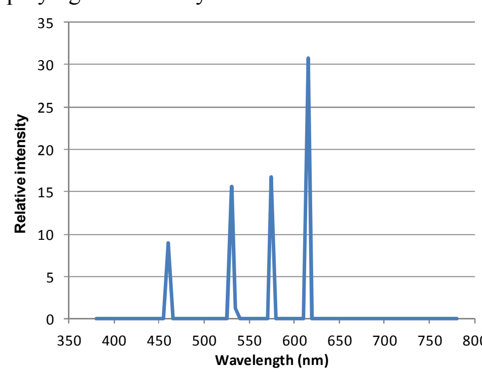



***Figure 1.*** *SPD of MWLER light (CT: 2856K, Ra: 90)*

## Extreme SPD of Light Source

We calculate some extreme light sources for specific purposes in addition to MWLER light; the light giving the largest color gamut, the light giving lowest impact for fine arts, the light keeping the dark adaptation and the light that can be used in clean room for semiconductor manufacturing.

The common approach to calculate such SPD is, firstly to define an evaluation function, and secondly set up CCT on the

Planckian locus (Daylight locus is not used regardless the definition) and CRI (if applicable), and then to execute Microsoft Excel Solver to optimize SPD either maximize or minimize the evaluation function. We use 5-nm increment in a range of 380 - 780 nm as variable under the condition of non-negative values.

(1) Largest color gamut (MGA light)

One of extreme lights is to boost the color saturation of objects as much as possible. It is empirically known that a light source having three peaks at R, G, and B gives higher saturation. Based on the concept used in Gamut Area Index (GAI) [2], we calculate the SPD of optimum light source which maximizes the saturation, or the area of the octagon formed by the eight color patches defined in CIE 13.3 in the *u'v'* chromaticity diagram [3]. The area is calculated by the sum of triangles formed by two adjacent color patches and the barycenter of the eight color patches. Here, we name such light Maximum Gamut Area light (MGA light). An example is shown in Figure 2 (a) for a CT of 3999K.

(2) Lowest impact to fine arts (Museum light)

CIE 157 defines damage functions with respect to wavelength for fine arts, which have more weight in the UV region. To minimize the impact for the fine arts, the convolution with the damage function should be minimized while maintaining a certain CRI and specified CCT. When a damage function is used as the evaluation function, and an Ra of 95 and a CT of 2856K are supposed, optimized SPD is shown in Figure 2 (b).

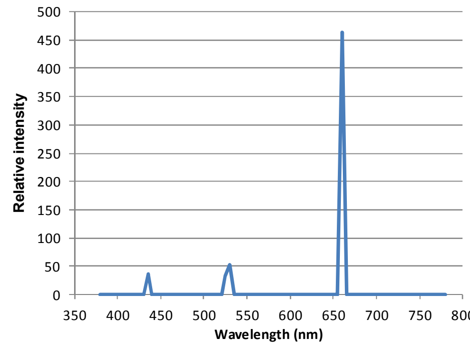
(3) Lowest impact to pupil (Dark Adaptation light)

It is known that pupil size is controlled by ipRGC, which has a peak at about 480 nm. At night, red light is often used in crew cabins of vessels to keep dark adaptation. Crews need to see charts for navigation and to see the outside to watch other vessels and obstacles. Thus red light is used because it does not have short wavelength. However under such light, it will be monochromatic, and is not comfortable. To have it both ways, when we use the sensitivity of ipRGC for the evaluation function, and an Ra of 50 and a CT of 2000K, the optimized SPD has three spikes as shown Figure 2 (c).

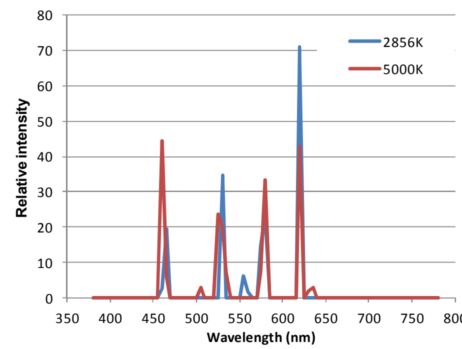
(4) Yellow lights in clean room (Clean Room light)

In clean rooms for semiconductor manufacturing, yellow light without the blue region. An ordinary solution is to put yellow filter on the top of fluorescent tubes. However, it will be nearly monochromatic and is not comfortable for workers under the circumstance. Thus, when we set the light amount 500 nm or under is set as the evaluation function, and an Ra of 50 and a CT of 2000K, the optimized SPD becomes Figure 2 (d).

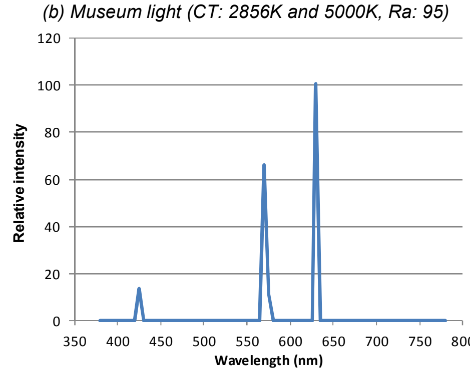
As shown here, all of the SPDs consists of multiple spikes. As the target CRI increases, the SPD is getting close to continuous as somewhat shown in Museum light, which consists of five spikes. Now a question arises: When we presume that future lights utilize such spiky SPDs, what kind of impact would be given to visual and camera systems? We test the impact by simulation as follows.



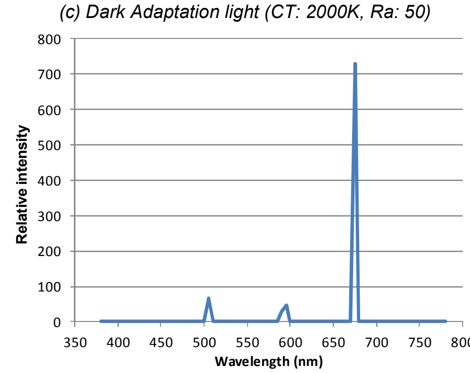

*(a) Maximum Gamut Area light (CT: 3999K)*




*(b) Museum light (CT: 2856K and 5000K, Ra: 95)*




*(c) Dark Adaptation light (CT: 2000K, Ra: 50)*




*(d) Clean Room light (CT: 2000K, Ra: 50)*

***Figure 2.*** *Examples of extreme SPDs*

## Simulation method

Due to the nature of light sources, colors under reference light (black body or day light) and testing light never are the same

**Table 1. Characteristics of light sources used in the simulation**

| Light source | F2 | F2_MWLER | F2_MGA | F7 | F7_MWLER | F7_MGA | F11 | F11_MWLER | F11_MGA | LED-A | LED-A_MWLER | LED-A_MGA | LED-B | LED-B_MWLER | LED-B_MGA | LED-C | LED-C_MWLER | LED-C_MGA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MWLER ratio | 81% | 98% | 28% | 73% | 100% | 34% | 84% | 99% | 29% | 82% | 100% | 33% | 69% | 97% | 26% | 73% | 98% | 27% |
| GAI(against BB) | 78% | 96% | 178% | 94% | 101% | 180% | 104% | 103% | 178% | 82% | 99% | 180% | 105% | 107% | 177% | 69% | 108% | 177% |
| LER | 336 | 408 | 116 | 254 | 348 | 119 | 337 | 397 | 116 | 291 | 353 | 118 | 297 | 419 | 112 | 298 | 398 | 111 |
| MWLER | 416 | | | 349 | | | 402 | | | 355 | | | 430 | | | 405 | | |
| *x* | 0.3721 | 0.3711 | 0.3711 | 0.3129 | 0.3136 | 0.3136 | 0.3805 | 0.3805 | 0.3805 | 0.3063 | 0.3073 | 0.3073 | 0.4384 | 0.4405 | 0.4405 | 0.4590 | 0.4459 | 0.4459 |
| *y* | 0.3751 | 0.3707 | 0.3707 | 0.3292 | 0.3237 | 0.3237 | 0.3769 | 0.3768 | 0.3768 | 0.3229 | 0.3175 | 0.3175 | 0.4010 | 0.4053 | 0.4053 | 0.4324 | 0.4069 | 0.4069 |
| CCT | 4223 | | | 6496 | | | 3999 | | | 6930 | | | 2950 | | | 2878 | | |
| Ra | 64.1 | 64.1 | -29.6 | 89.7 | 89.7 | -22.5 | 82.8 | 82.8 | -29.5 | 80.4 | 80.4 | -23.0 | 77.4 | 77.4 | -31.0 | 91.9 | 91.9 | -32.0 |
| R1 | 56 | 83 | -34 | 88 | 97 | -26 | 98 | 98 | -32 | 83 | 98 | -27 | 78 | 98 | -29 | 92 | 99 | -31 |
| R2 | 77 | 74 | 83 | 92 | 88 | 88 | 93 | 87 | 84 | 99 | 85 | 87 | 82 | 85 | 78 | 94 | 89 | 77 |
| R3 | 90 | 30 | 0 | 92 | 81 | 18 | 50 | 55 | -12 | 87 | 47 | 23 | 82 | 43 | -48 | 94 | 85 | -48 |
| R4 | 57 | 66 | -76 | 89 | 93 | -82 | 88 | 88 | -71 | 63 | 87 | -85 | 77 | 82 | -49 | 90 | 93 | -51 |
| R5 | 59 | 61 | -18 | 89 | 88 | -17 | 87 | 83 | -14 | 78 | 81 | -20 | 74 | 77 | -3 | 90 | 92 | -5 |
| R6 | 67 | 39 | 68 | 88 | 82 | 59 | 77 | 74 | 68 | 91 | 68 | 56 | 71 | 60 | 68 | 92 | 89 | 69 |
| R7 | 74 | 86 | -58 | 94 | 97 | -41 | 89 | 94 | -60 | 77 | 95 | -39 | 85 | 92 | -64 | 95 | 93 | -64 |
| R8 | 33 | 74 | -201 | 86 | 92 | -180 | 79 | 83 | -201 | 65 | 83 | -179 | 70 | 82 | -201 | 89 | 97 | -202 |
| R9 | -84 | 0 | -467 | 57 | 57 | -500 | 25 | 25 | -455 | 19 | 19 | -509 | 26 | 26 | -404 | 72 | 72 | -403 |
| R10 | 45 | -3 | 52 | 78 | 64 | 34 | 47 | 41 | 62 | 94 | 34 | 21 | 54 | 27 | 88 | 84 | 68 | 85 |
| R11 | 46 | 23 | -90 | 85 | 81 | -105 | 72 | 71 | -80 | 61 | 69 | -112 | 73 | 45 | -45 | 88 | 89 | -47 |
| R12 | 54 | -22 | 11 | 85 | 20 | -10 | 53 | 12 | 18 | 53 | 4 | -18 | 45 | -2 | 62 | 78 | 41 | 64 |
| R13 | 60 | 78 | -3 | 89 | 95 | 7 | 97 | 95 | -1 | 90 | 94 | 5 | 77 | 93 | -7 | 92 | 91 | -9 |
| R14 | 94 | 53 | 36 | 95 | 84 | 53 | 67 | 69 | 30 | 93 | 67 | 57 | 89 | 59 | 13 | 96 | 86 | 12 |
| R15 | 47 | 99 | -82 | 86 | 87 | -70 | 96 | 91 | -82 | 77 | 84 | -69 | 76 | 92 | -87 | 89 | 93 | -88 |

unless the testing light has an Ra of 100. Since this issue cannot be avoided, we evaluate the error between appearance with CIE color matching functions (CMFs) and reproduced color by testing spectral sensitivity under various light sources. For simplification, we use two types of extreme light sources: MWLER light and MGA light.

Step 1: Preparation of light source and extreme SPDs

a) Choose existing light sources

We choose the following six lights: F2, F7, F11 [3], LED-A, LED-B, and LED-C [4] as existing lamps and benchmarks. F2 is a Cool White Fluorescent lamp (4223K), F7 is a D65 daylight simulator (6496K), and F11 is three-peak type fluorescent (3999K). LEDs A, B and C are chosen from white LEDs, which have blue LED with yellow phosphor and are readily found in the market. These LEDs have different CCTs: 6930K, 2950K, and 2878K, respectively. These are shown in Figure 3.

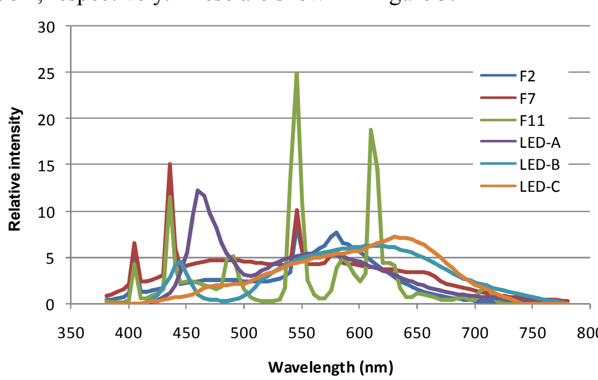



***Figure 3.*** *SPD of lights (F2, F7, F11, LED-A, -B, -C)*

b) Find MWLER light for each light source shown in a)

Although the discussion on new CRI is a hot issue now, we use conventional CRI defined by CIE 13.3. We employ R9 in addition to Ra, because, in practice, the value of R9 is often combined with Ra to show color quality of reddish colors, such as skin, in the lighting industry. Thus we basically use both Ra and R9 which are identical to the existing lamps for test. In case of the F2 lamp, we use R9=0 because the original R9 value of F2 is too low. The SPDs are shown in Figure 4 (top). Note that SPD is composed of four or five spikes.

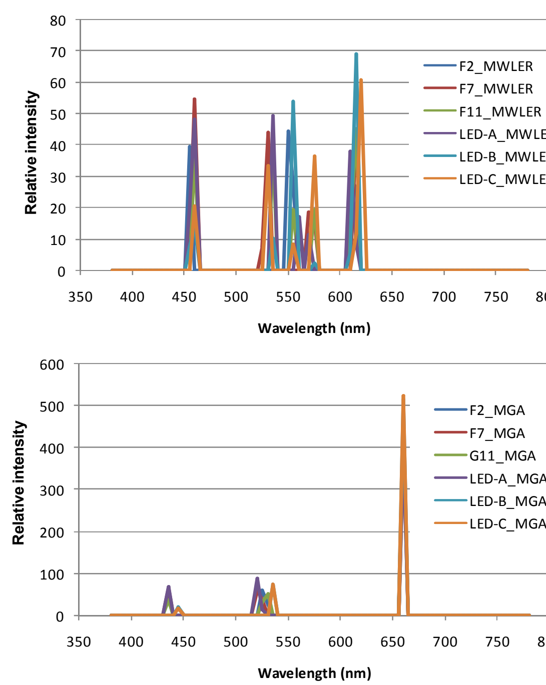



***Figure 4.*** *SPDs of MWLER light (top) and MGA light (bottom)*

c) Find MGA light for each light source shown in a)

These SPDs are shown in Figure 4 (bottom). As expected, every SPD is composed of three spikes: R, G, and B. Note that the resulting R spike becomes a very high intensity.

The characteristics of these light sources are summarized in Table 1. Here, MWLER ratio is calculated by LER over MWLER. GAI indicates the ratio of the area formed by the CIE 13.3 eight patches under black body radiation with the same CCT. LER is luminous efficacy of radiation as defined. MWLER indicates the MWLER having the same CRI (Ra) and CCT with existing lamps: F2, F7, F11 and LEDs. R15 is skin color of Japanese defined in Japan Industrial Standards, JIS Z 8726 [5]. We did not use daylight for the calculation of CRI to avoid discontinuity regardless the definition of CIE 13.3. Light source "xx_MWLER" is calculated with the consideration of R9 as mentioned before. Thus LER ratio for them is not 100%.

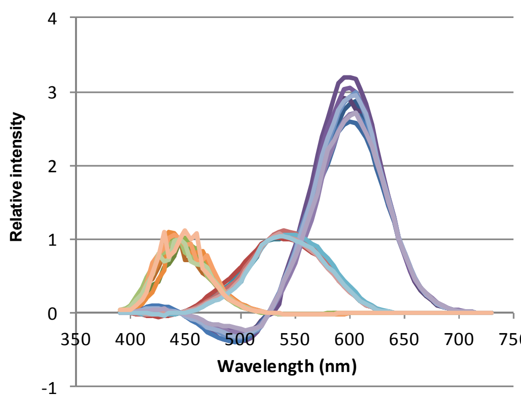



***Figure 5.*** *Stiles and Burch color matching functions*

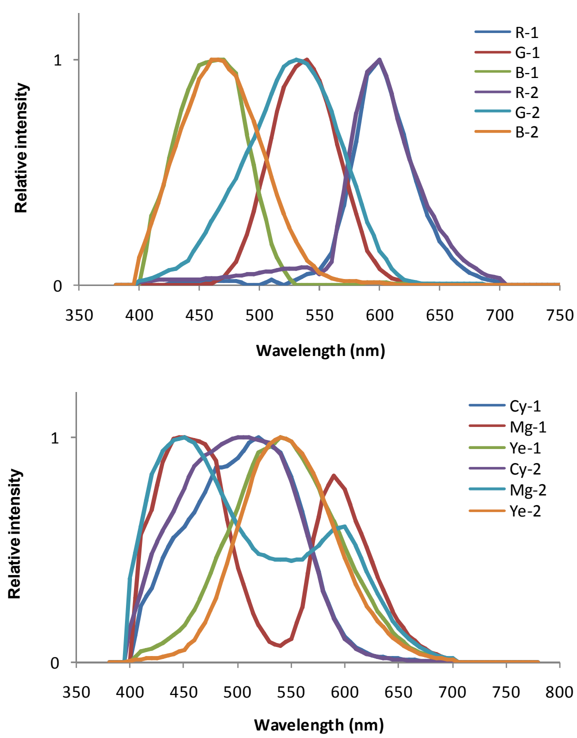



***Figure 6.*** *Camera sensitivity (Top: RGB, Bottom: CMY)*

Step 2: Sensitivity of human visual system and camera

As for a variation of color matching functions, we use the 10 sets of CMFs given by Stiles and Burch as shown in Figure 5 [6]. The data is interpolated to 5 nm increments. As for a variation of camera sensitivity, we use two sets of RGB camera sensitivity and two sets of CMY camera sensitivity as shown in Figure 6 [7].

Step 3: Optimization of color matrix for reproduction

Even though Ra is identical to the testing light, the apparent color of objects under both lights will be different. Since our goal is not to evaluate the deficiency of CRI, we evaluate relative difference between apparent color using CIE color matching functions and Stiles and Burch color matching functions and camera sensitivity. We set the ground truth using Macbeth color checker under black body radiation. Both Stiles and Burch CMFs and camera sensitivity are handled equally – an optimized matrix is applied. The 3x3 matrix is optimized to give the minimum average color difference for a Macbeth Color Checker under black body radiation in the CIE L*a*b* color space anchoring virtual perfect diffuser as white. The tristimulus values calculated by Stiles and Burch CMFs and RGB/CMY camera values are converted into XYZ using the 3x3 linear matrix. Therefore in this simulation, the error of automatic color balance, which is the most influential parameter in practice, is eliminated. Also, the selection of a set of primaries of CMFs is eliminated [8].

## Result

### *Color shift and error*

Two samples of target and reproduced colors are shown in Figure 7. Red "+" is the target (black body, BB light hereafter) and red "o" is the reproduced color. Green "x" is the appearance under existing lamp and green "o" is the reproduced color under existing lamp. Blue indicates MWLER light (with R9 concerned) and orange indicates MGA light respectively. It is observed that MGA light gives saturated colors toward the R-G direction while others stay similar a*, b* values.

### *Color differences by sensitivity*

We evaluate the color difference between targeted and reproduced colors for 10 Stiles and Burch CMFs and 4 sets of camera sensitivity under existing lamp, BB light, MWLER light and MGA light as shown in Figure 8. We evaluate average error and maximum errors for all of the combinations.

As shown in Figure 8, all sets of camera sensitivity give large error, and especially for spiky light sources (MWLER light and MGA light), it exposes extremely large average errors. As opposed to camera sensitivity, the color error caused by variation of CMFs stays within about 2 in ΔE*ab except for CMF5.

### *Color difference by light sources*

Figure 9 indicates the color error with respect to light sources. In case of CMF, average errors range from 1 to 3 in ΔE*ab. However, in case of camera sensitivity, it is found that the average error ranges from 1 to 11 in ΔE*ab and the worst error becomes enormous.

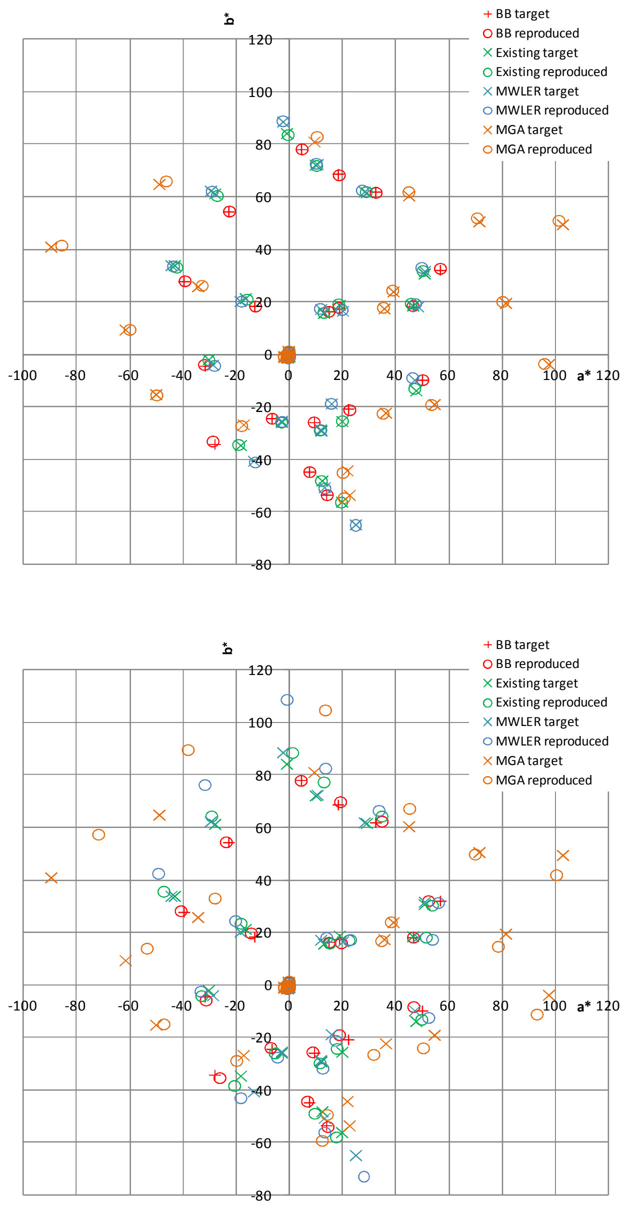



***Figure 7.*** *The color error under F11 and associate light sources with a set of Stiles and Burch CMFs (top) and RGB camera sensitivity (bottom)*

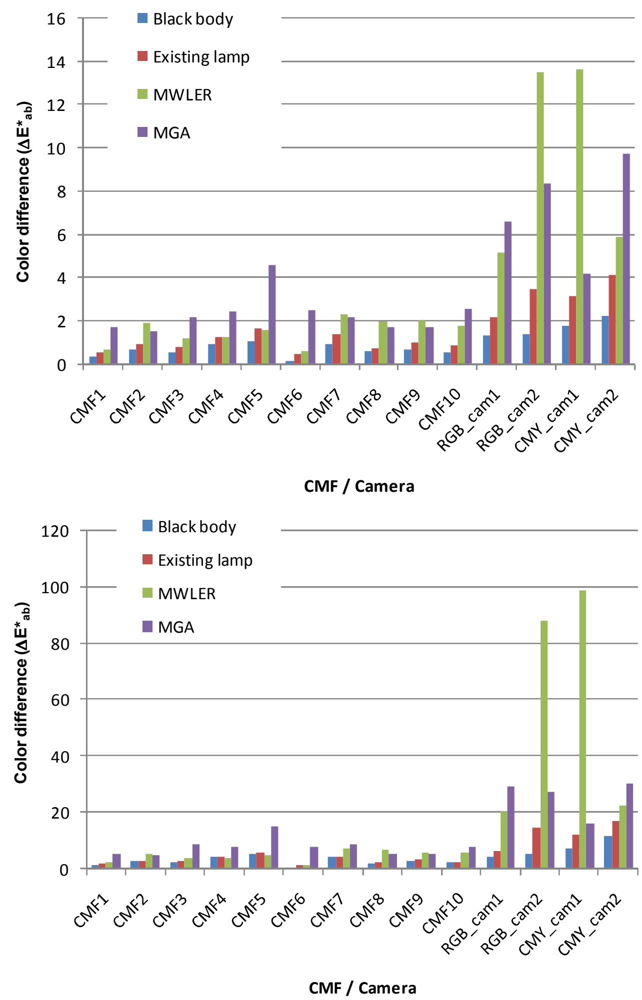


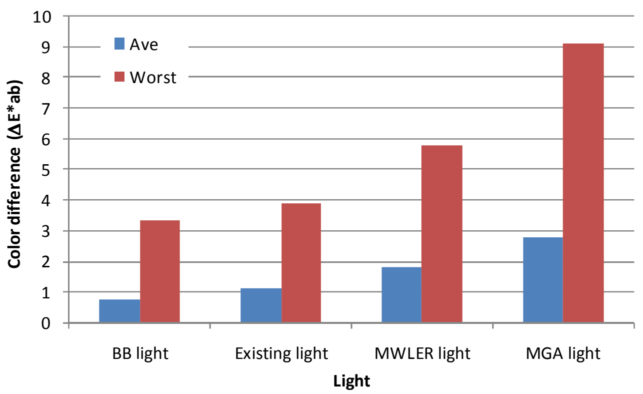

***Figure 8.*** *Color errors of camera sensitivity and Stiles and Burch CMF (top: average, bottom: worst)*

## Discussion

Color errors with different CMFs are similar in general within ΔE*ab=2, while CMF5 shows somewhat large error. It means MWLER light, or energy saving light, and MGA light, or saturation-boosting light, composed of spikes can be acceptable in the sense of spectral matching with CMFs. It could be used without giving bad color reproduction for a variation of human eyes. MGA light gives more error, but it still seems tolerable. In this simulation, the data by Stiles and Burch is used, but other CMF data is available such as Sarkar et al [9], CIE 170 [10], etc. The evaluation using such data will be future work.

Thus, in this simulation, such extreme lighting sources can be practical if they could be realized. Of course, at this moment, the combination of tunable laser or very special device may be the only approach. We hope that the advancement of material and device technologies realizes such light sources. This simulation uses an extreme case, but since the actual light source may be broader than the one we used, color errors will be reduced.

However, the impact to camera sensitivity is significant. The worst errors exceed 30 in ΔE*ab (in some cases, over 50). It implies that under such an extreme light source, the color reproduction of a camera will be imploding. There may be two approaches to prevent such situations. The best approach is to adjust sensitivity to be close to the Luther condition, which is a linear transformation of CMF. However, in practice, it may not be easy due to production and material issues. Also, it would increase the chroma noise due to overlap of sensitivities [11]. The second approach is to add a switch to choose the right color matrix to compensate for the color errors. However, how to detect such light sources – maybe requiring a special device, will be challenging.



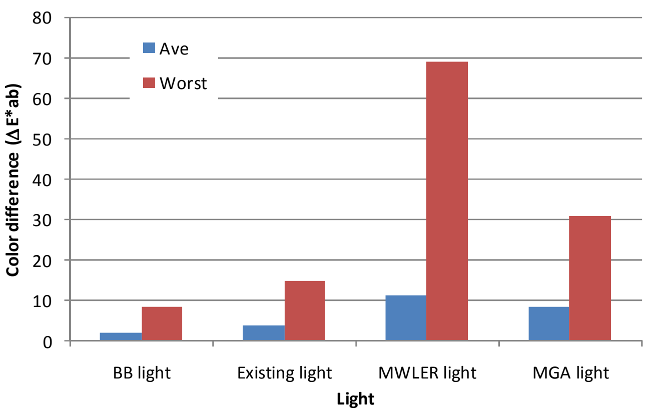




***Figure 9.*** *Average and worst color errors with respect to light (top: Stiles and Burch CMF, bottom: camera)*

## Conclusion

We have demonstrated that SPD of extreme light designed for a specific purpose will be spiky. Then we evaluated the drawback of virtual extreme energy saving lights and extreme saturated lights as compared with typical light sources currently used. Because these extreme light sources are composed of spiky SPD, they were thought to output light which is very sensitive for human eyes. However our simulation results give a reasonable error – which may be tolerable by ordinary observers.

Since, in practice, the light source may not have sharp spikes as tested in our simulation, the level of super-sensitivity will be limited. On the other hand, the error caused by the deviation from the Luther condition of cameras is remarkable and may not be tolerated. The best approach is to satisfy the Luther condition, but it would not be feasible. The second approach may be to switch color rendering matrix depending on light source.

The advancement of lighting technologies will give more flexibility to design a light source for a special purpose. Since saving energy is a pressing issue now, and the technology development is quick, sooner or later, cameras will need to handle new types of lighting.

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