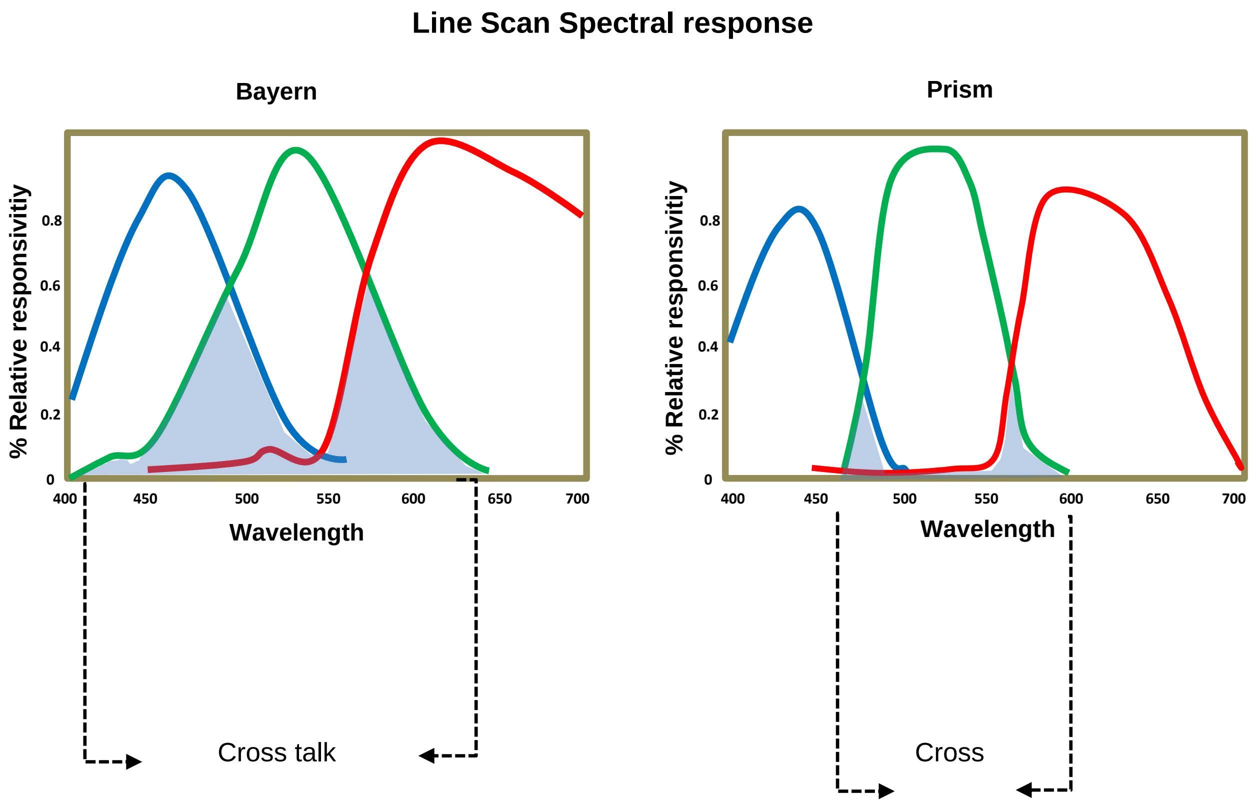
Spectral sensitivity curves of cameras

Whitepaper

The manufacturers of color cameras pursue different concepts in the design of spectral sensitivity curves.

For example, different line scan prism manufacturers compare two possible curves of these curves in their advertising and argue that the steeper flanks should enable better color reproduction with greater selectivity.



The argumentation seems conclusive - is it also correct?

In order to be able to judge this statement, it is necessary to take a look at the basics.

The colorimetry still most commonly used today is based on the so-called CIE standard observer of 1931. At that time a spectral sensitivity curve for the color-sensitive receptors of the eye was determined by a comparative evaluation of color areas with 3 spectral lines. These curves were then transferred to the CIE normal-valence system.

The entire colorimetry still refers to this system today. The color spaces used today, such as sRGB, AdobeRGB, eciRGB and CIELAB, are all defined using the CIE standard valence system.

Each RGB camera supplies a color triple {R, G, B} as answer for a given color. This RGB value is a device-specific description of the submitted sample and cannot be interpreted without reference to exactly this camera.

This is necessary, however, if you use

- the distance of the measured color to a color specified in a standard system

  or

- would like to assign a calorimetrically defined distance dimension to the color difference of several samples to each other.

Both colours and colour spacings are always defined in relation to the CIE standard valence system, as explained above.

It follows from that it is necessary to somehow transfer the device specific RGB values of the camera into this system.

In 1927, Robert Luther first formulated the necessary condition for a technical recording device to be able to reproduce the visual behaviour of the eye. This is the case when the spectral sensitivity curve consisting of filter and spectral characteristic of the receiver differs from the standard spectral value curves by only one factor k.

$$\tau(\lambda)_X = k_X \cdot \frac{\bar{x}(\lambda)}{s(\lambda)}$$ für die *Rotorangefilter-Analyse*,

$$\tau(\lambda)_Y = k_Y \cdot \frac{\bar{y}(\lambda)}{s(\lambda)}$$ für die *Grünfilter-Analyse* und

$$\tau(\lambda)_Z = k_Z \cdot \frac{\bar{z}(\lambda)}{s(\lambda)}$$ für die *Blauviolettfilter-Analyse*

mit

However, this condition is not met by any standard RGB camera. The reason is that the filters are optimized with regard to the output color space.

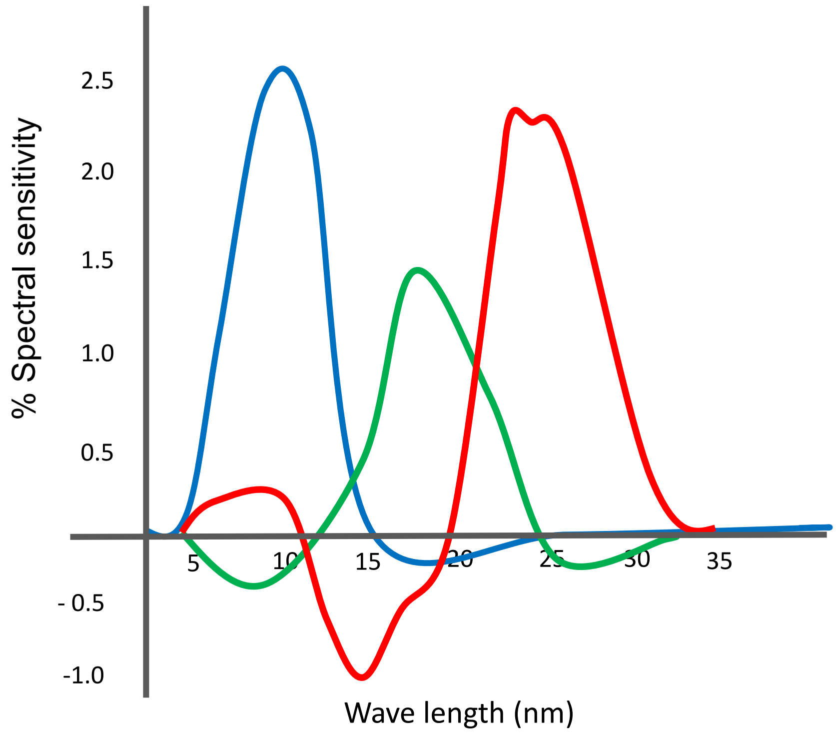
For example, for the widely used sRGB standard, this is based on the primary colors typical for monitors at the time of definition and thus ensures that a camera output image produces a usable color impression on the monitor without conversion.

A good filter characteristic in an industrial environment should meet both requirements as far as possible.

This could be achieved by the fact that the spectral curves are fundamental metamers of the normal spectral value curves. This condition is fulfilled if the filter function can be mapped to the standard spectral value function by a non-singular 3x3 matrix.

The transformation of the standard spectral value curves into filter curves for common output color spaces generally leads to curves with negative components that cannot be realized physically.

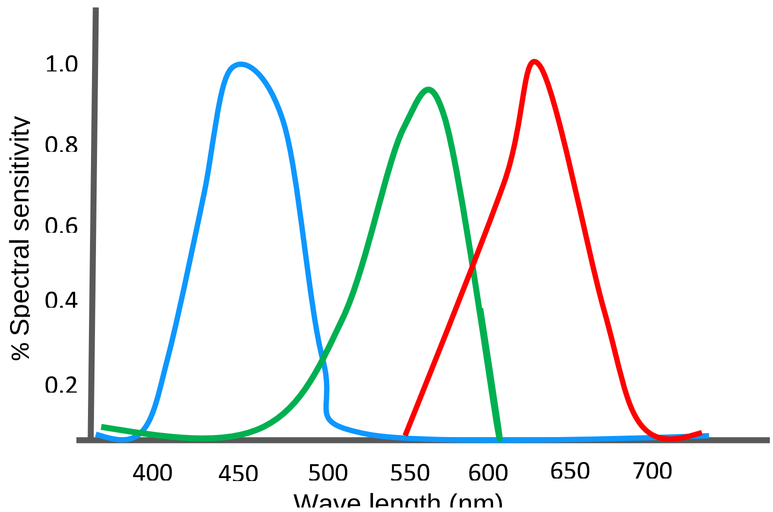
Theoretical filter function for sRGB output



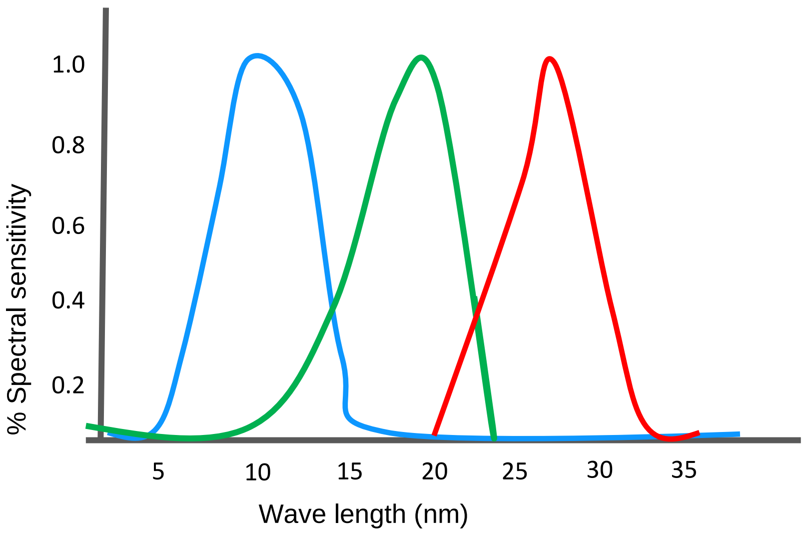
Actual realised filter functions always represent a compromise between theoretical consideration and practical feasibility.

Three examples for comparison

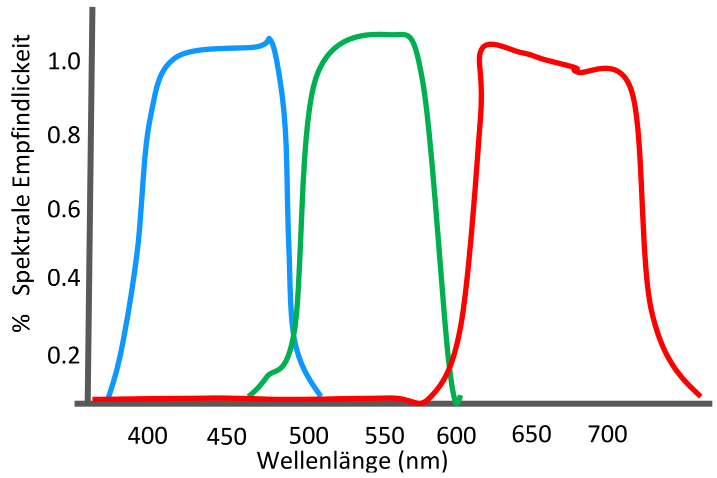
1. Filter curves of a well-chosen filter characteristic



2. Filter curves according to the standard camera model of the EBU in document TECH 3353



3. Aus from Prims camera



The curves differ essentially in the slope steepness. Due to the dichroic filters used, the curves in 3 are much steeper than in 1 and 2.

The camera manufacturer with curves 3. argues that the steepness of the flanks would allow a good color separation.

None of the two curves meets the Luther criterion mentioned above, which would allow a correct transformation of the RGB values into the standard color space.

For which of the two curves does this succeed with fewer deviations?

Black Metamere

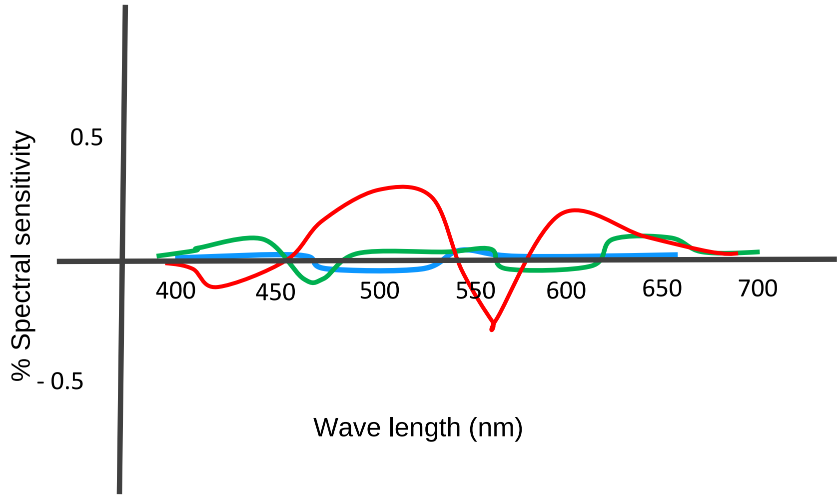
Behind this question is the question which curve comes closest to a fundamental metamer of the norm spectral value curves. This question will be answered with the help of the Cohen matrix.

This can be understood as a projector that projects the filter function of the sensors onto the fundamental metamers of the standard spectral value functions. These functions are divided into parts, which lie in this space spanned by the metamers and the perpendicular part to it. This vertical part is called the black metamer. The name derives from the fact that in the investigation of metameric behaviour of color spectra, this is the part of the spectrum that does not contribute to color discrimination in an observer.

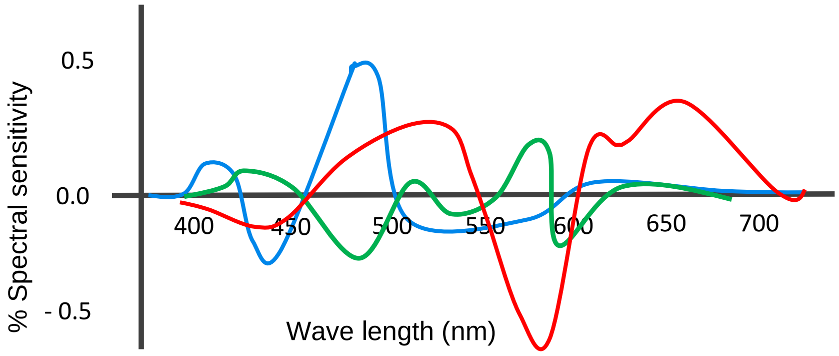
In the technical processing of color information, the black metamer of the sensor spectrum is the portion of the signal that "disturbs" the mapping to the standard spectral values. The lower this proportion is, the better the transformation succeeds.

Here are the spectral curves of the black metamere for the two color filter functions.

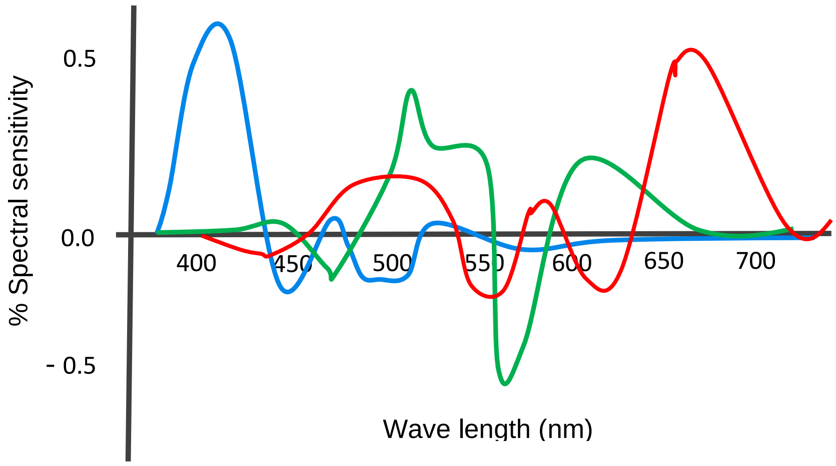
Spekt Gradient Black - Metamaer Filter 1



Spekt Gradient Black – Metamer Filter 2



Spekt Gradient Black – Metamer Filter 3



The signal component of the disturbing black metamer results from the inner product of the color spectrum and the spectral black metamer curves. In curves 3, this is significantly larger than in curves 1 and 2, especially in the critical green component. This interference component cannot be completely corrected without knowledge of the color spectrum.

Simulation with ColorChecker

In addition in a reproduction of the scanning process from the spectra β of the n=24 color fields and the spectral sensor sensitivities S of the associated RGB values calculated. An Illumination with a D50 characteristic is assumed.

$$rgb_n = (S_{r,g,b} * D50) \cdot \beta_n$$

The RGB values obtained in this way are mapped to the XYZ values with a 3x3 matrix M and the statistics of the differences in the color distance measure ΔE¬ are determined according to CIE2000. The matrix M is determined using the least squares method.

These error statistics belong to the two sensor variants:

Spectral sensitivity curves 1:

Mean ΔE	Q95	Max ΔE
0.673978	1.4768	2.11624

Spectral sensitivity curves 2:

Mean △E	Q95	Max △E
2.11357	4.2178	4.66706

Spectral sensitivity curves 3:

Mean △E	Q95	Max △E
2.85943	6.5727	10.5661

As expected, the RGB values obtained with filter curves 1 can be transferred to the standard color space with the smallest deviations. While curves 2 are still acceptable, the high maximum error of curve 3 is critical.

Overall view

The dE deviations can be significantly reduced with nonlinear methods. However, these always also result in a greater sensitivity of the transformation for small deviations of the process parameters.

However, it should also be mentioned that this transformability is only one aspect of the filter design. When comparing the curves, it is obvious that the areas under the curves at 2. and 3. are significantly larger. This means that the available light is better utilized, which can result in a better signal-to-noise ratio.

Literature:

1. EBU TECH 3353 Development of a „Standard” Television Camera Model implemented in the TLCI-2012
2. White Paper Jai: How does prism technology help to achieve superior color image quality
3. Jozef Cohen: Visual Color and Color Mixture: The Fundamental Color Space

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