Colourimetric scaling of luminance and chromaticity of *rgb** images on SDR and HDR displays using a TUB colour-vision model

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or see *publications* under http://color.li.tu-berlin.de/XY91FEN.html

Content

Note: This paper contains parts of the previous TUB publication dislum25d.pdf (see XY91FDE). The present new work will be named dissca25.pdf on the Internet.
Sections 4 to 6 contain new research results. For example, approximately:

ln $(L^*_{CIELAB} / L^*_{CIELABu})$ = log (Y/Y_u) or **$L^*_{CIELABr} = e^x$** with **x_r =log(Y/Y_u),** compare **$F_{ab}(x_r)$** in Figure 1 and in Sections 4 and 7: **$L^{**}_{CIELAB,u} = (e^{X_r} - e^{-X_r}) / (e^{X_r} + e^{-X_r})$** for the **colour appearance.**

1. Introduction

New displays for the High Dynamic Range (HDR) lead to new possibilities for the output of scene luminance compared to the Standard Dynamic Range (SDR).

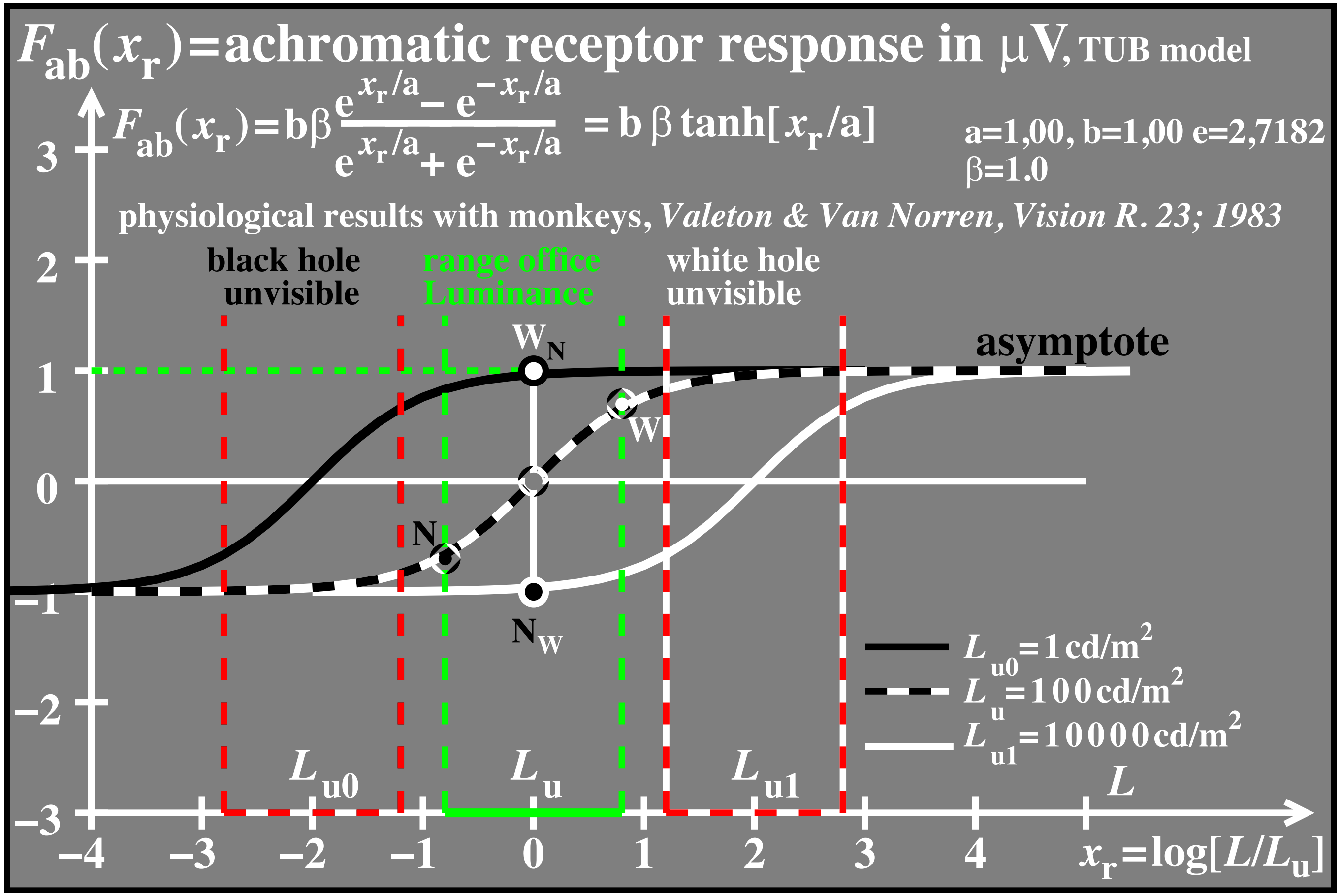
Analogue photography uses at least 4 logarithmic luminance units. In negative film, luminance was encoded as density proportional to the logarithmic luminance. The present digital photography can also store at least 4 logarithmic luminance units. In addition, the information is directly available as a digital image file.

For each encoding of scene luminance by a potential, logarithmic or hyperbolic function, inverse decoding regenerates the luminance and chromaticity of the display. However, there is always a mixture of the emitted display light and the ambient light. For example, this contrast reduction is taken into account in ISO 9241-306 and not in ISO 22028-5.

For the application, the appropriate encoding and inverse coding (decoding) according to the properties of the human visual system is important. Proposals and solutions are discussed below.

Figure 1 shows an approximation of the visual excitations of monkeys by a hyperbolic function. The literature is indicated in the figure. The visual excitations are always in the range of -1 to 1. They were measured for four logarithmic units of adaptation and for about 6 logarithmic units of sample luminance.

2. TUB model of achromatic physiological excitations and psycho-physical data

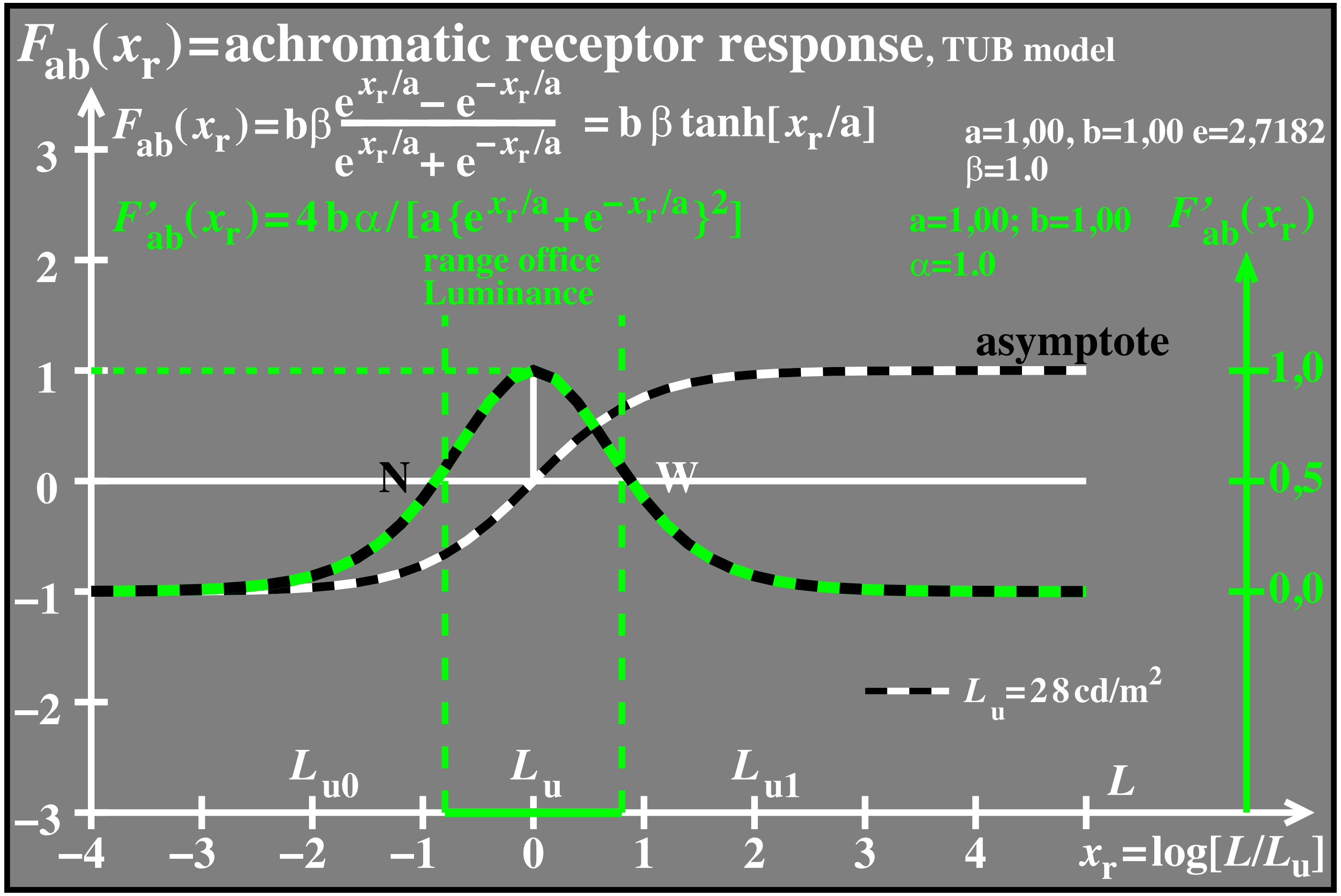


eeg00–5n

Figure 1 Physiological excitation curves of monkeys for three adaptation levels

To download this image, see http://color.li.tu-berlin.de/eeg0/eeg00-5n.pdf

The literature, the sample luminance range and the adaptation level are given in the figure.
The samples Black N, Grey U and White W are shown in the area of office luminance.



eeg00−3n

Figure 2 Physiological excitation curve and derivative for the office luminance range

To download this image, see http://color.li.tu-berlin.de/eeg0/eeg00-3n.pdf

The *relative* uminance should be used. All physiological excitation curves in Figure 1 are similar for different levels of adaptation. ISO 9241-306 defines L_u=*28* cd/m^2 for grey U in offices.

Mathematical equations of hyperbolic functions

See: ***Handbook of mathematical functions, NBS, USA, Sec. 4.5***

$$F_{ab}(x_r/a)=b\tanh(x_r/a)=b\,\frac{e^{x_r/a}-e^{-x_r/a}}{e^{x_r/a}+e^{-x_r/a}} \qquad [1]$$

$$\frac{dF_{ab}(x_r/a)}{dx_r}=\frac{4b}{a[e^{x_r/a}+e^{-x_r/a}]^2} \qquad x_r=\log(L/L_u) \quad dx_r/dL=\ln(10)/L \qquad [5]$$

$$\frac{dF_{ab}(x_r/a)}{dx_r}\,\frac{dx_r}{dL}=\frac{4b}{a[e^{x_r/a}+e^{-x_r/a}]^2}\,\frac{\ln(10)}{L} \qquad [6]$$

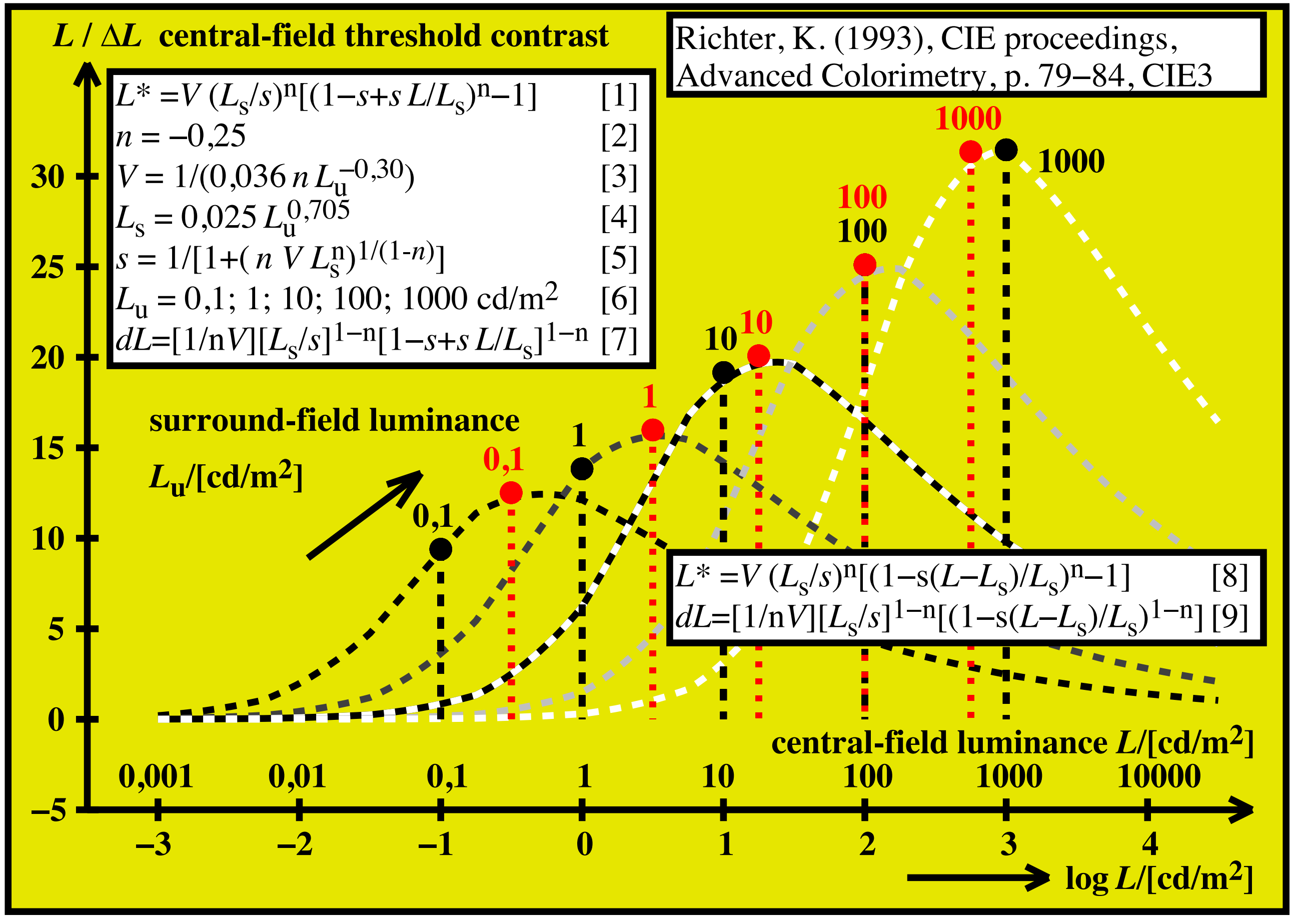
$$\frac{L}{dL}=\frac{4b\ln(10)}{a[e^{x_r/a}+e^{-x_r/a}]^2} \qquad dL=\frac{a[e^{x_r/a}+e^{-x_r/a}]^2 L}{4b\ln(10)} \qquad [7]$$

fek01–7n

Figure 3: Receptor-response curves are described by hyperbolic functions

To download this image, see http://color.li.tu-berlin.de/fek0/fek01-7n.pdf

The derivation of $F_{ab}[\log(L/L_u)]$ is proportional to the luminance contrast ($L/\Delta L$). If this contrast is constant (*Weber-Fechner law*), then the excitation curve is a straight line.



ees01−2n, ees10−2a

Figure 4 Psycho-physical luminance contrast for achromatic colours and 5 adaptations

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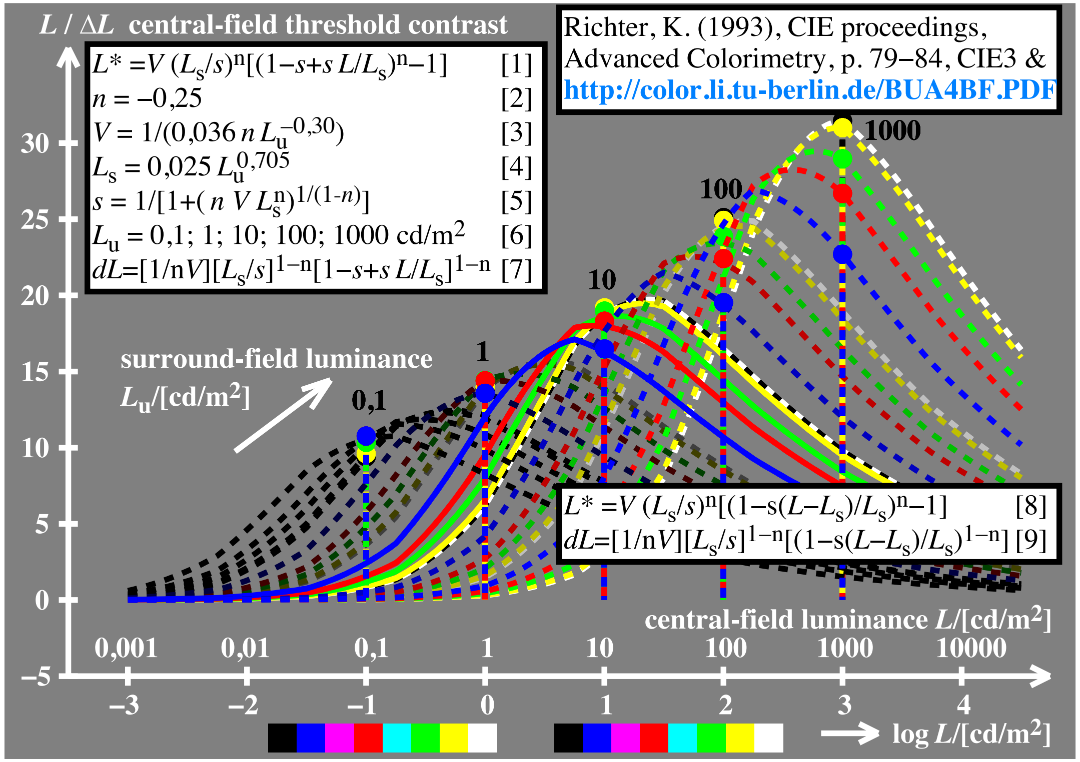
On the linear ordinate, this contrast increases by about 20% with a luminance change from 100 to 1000 cd/m^2. In the defined HDR luminance range between 200 and 1000 cd/m^2 according to ISO 22028-5, the contrast increases by about 10%. This may not be visible in most applications.



ees90−2a

Figure 5 Psycho-physical luminance contrast for achromatic and chromatic colours

To download this image, see http://color.li.tu-berlin.de/ees9/ees90-2a.pdf

For chromatic colours compared to achromatic colours, a shift in luminance contrast *(L/ΔL)* is assumed. For the RGBY display colours, the luminance according to IEC 61966-2-1 is used. The appearance of the 8 colours in the figure is almost constant over a wide luminance range and therefore shown twice. With a luminance change between 100 and 1000 cd/m^2 (factor 10), the contrast sensitivity changes from 25 to 30 (factor 1,2). For all RGBY colours, the maximum contrast is shifted to a lower luminance.

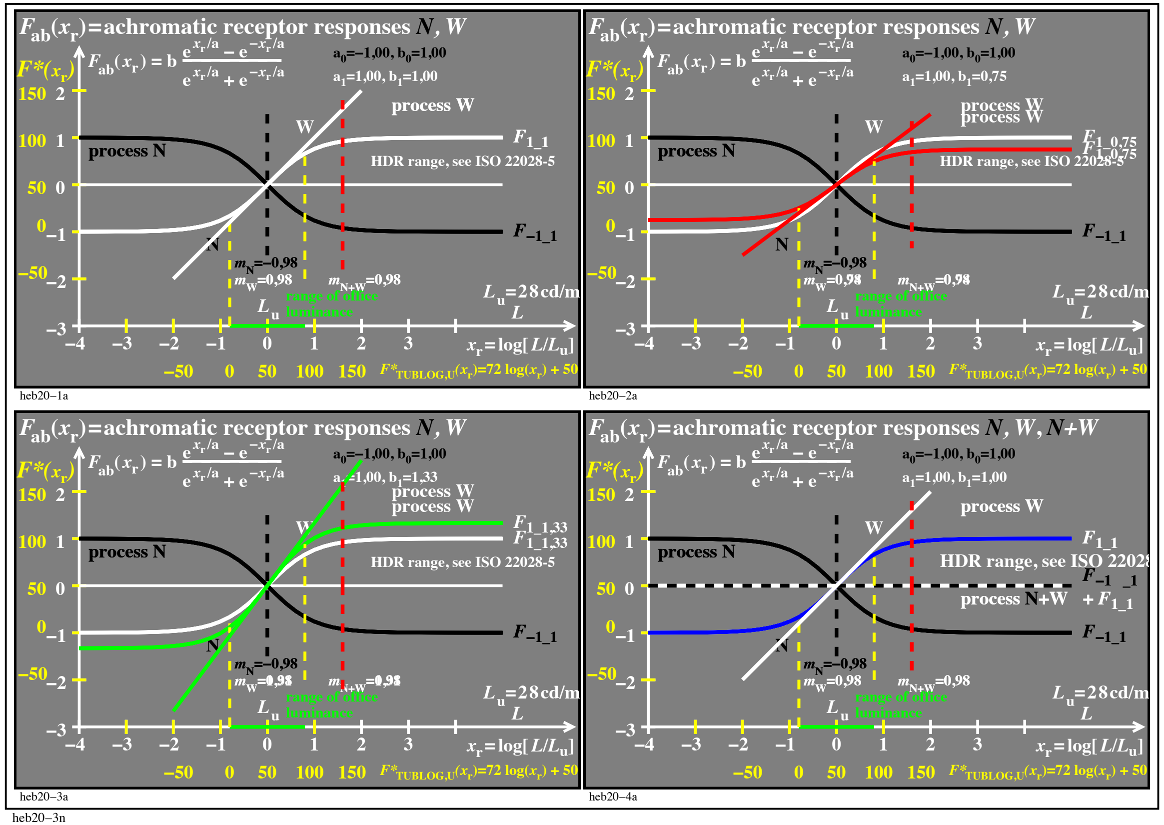


Figure 6: Model of physiological excitation functions with two parameters *a* and *b*

To download this image, see http://color.li.tu-berlin.de/heb2/heb20-3n.pdf

For *relative* excitation it is valid log (L/L_u) = 0. Parameter b changes the contrast between W and N. For b=3/4 *(red)* the contrast is smaller and for b=4/3 *(green)* it is greater compared to b=1 *(white).* Accordingly, the slope is smaller and larger compared to b=1. For the HDR range, 90<=Y<=450 applies, see white and red vertical dashed line. In image technology, the values 0 <= *rgb** <= 1 describe the lightness between N and W. For the HDR range, *rgb** is > 1.

3. Definition and output of *pdf*-test charts with HDR-*rgb** values in 2 use cases

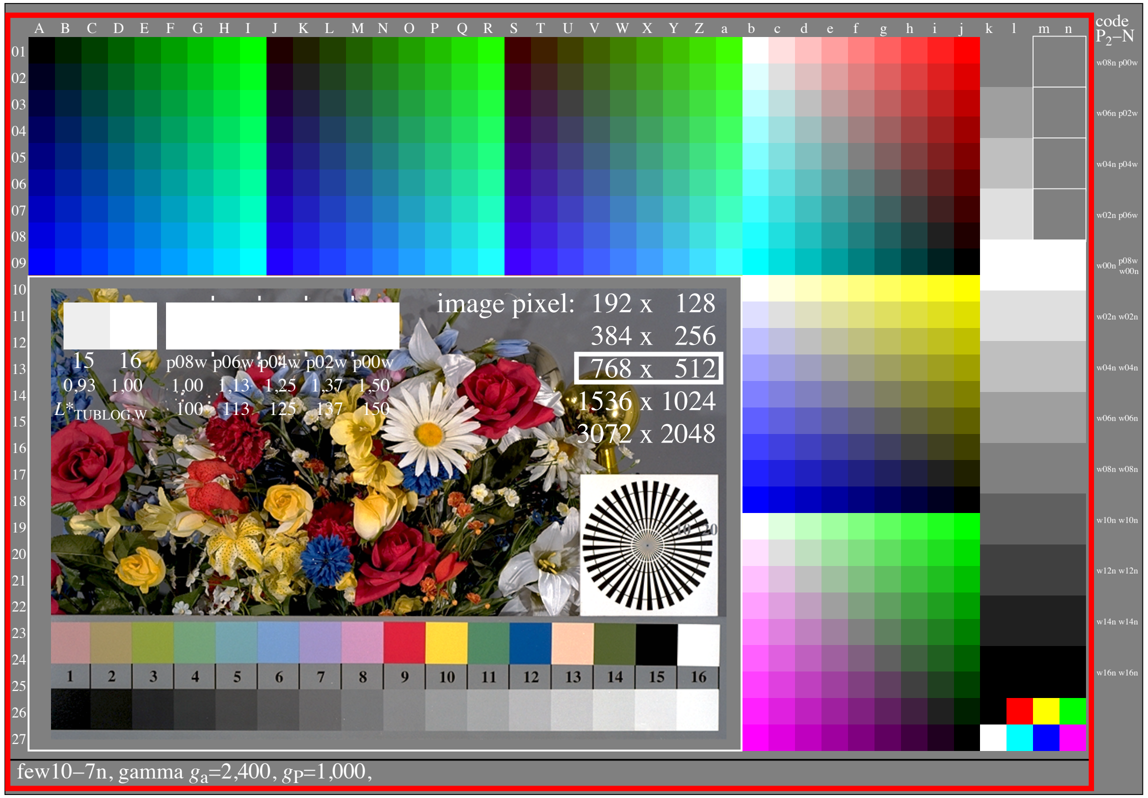


Figure 7: Output of the test chart with flower image of [1] on an SDR display with white *W*

To download this image, see http://color.li.tu-berlin.de/few1/few10-7n.pdf

The output of the *pdf* file of Figure 7 produces 5 white identical samples in the range of diffuse white (W) to peak white (P2). In the *pdf* file, the values 0 <= *rgb** <=1,5 are proportional to the lightness values 0 <= $L^*_{\text{TUBLOG,W}}$ <= 150. In pdf files, all values *rgb**>=1 are clipped to the value 1,0 by default. However, for the entire luminance range diffuse black N to peak white P2, all *rgb** values of lightness

$L^*_{TUBLOG,W}$ up to 150 can be included in pdf file. Division of the *rgb** data by a factor of 1,5 also shows the 5 different white samples W-P2, see Figure 8. However, all other colours then appear too dark.

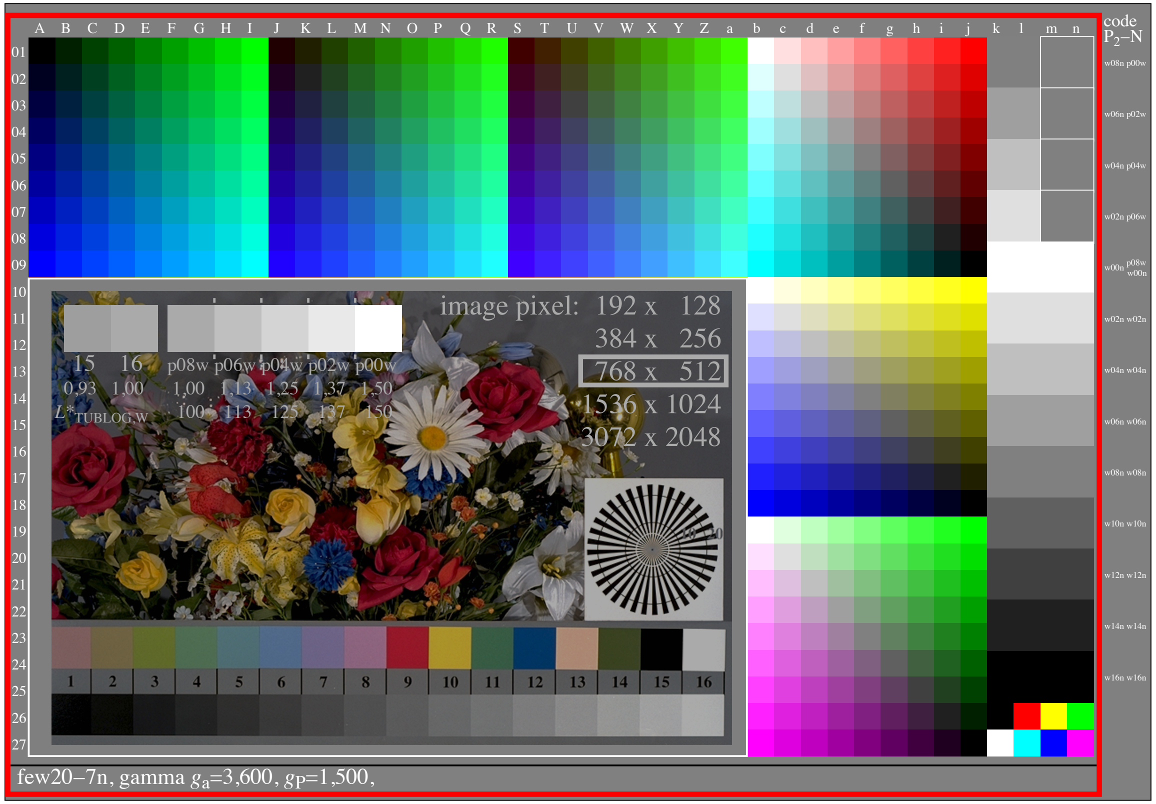


Figure 8: Output of test chart and flower image from [1] to SDR display with white *W*

To download this image, see http://color.li.tu-berlin.de/few2/few20-7n.pdf

The standard flower motif according to ISO 9241-306 looks darker. The white W=w00n=p08w corresponds in luminance and lightness to the surface colour white W of the step 16. However, the luminance of the display can be increased by a factor of 5 from 200 to 1000 cd/m^2. Then the luminance of the flower motif in Figures 7 and 8 is the same. However, in Figure 8, the 5 levels in the

W-P2 area are the same as intended. They do not appear the same as in Figure 7, so values rgb*>=1 in *pdf* files are used to store and visualize colours in the HDR range.

4. CIELAB, IECsRGB. and TUBJND: ln*(L^*_{CIELAB})* relation with physiological excitation

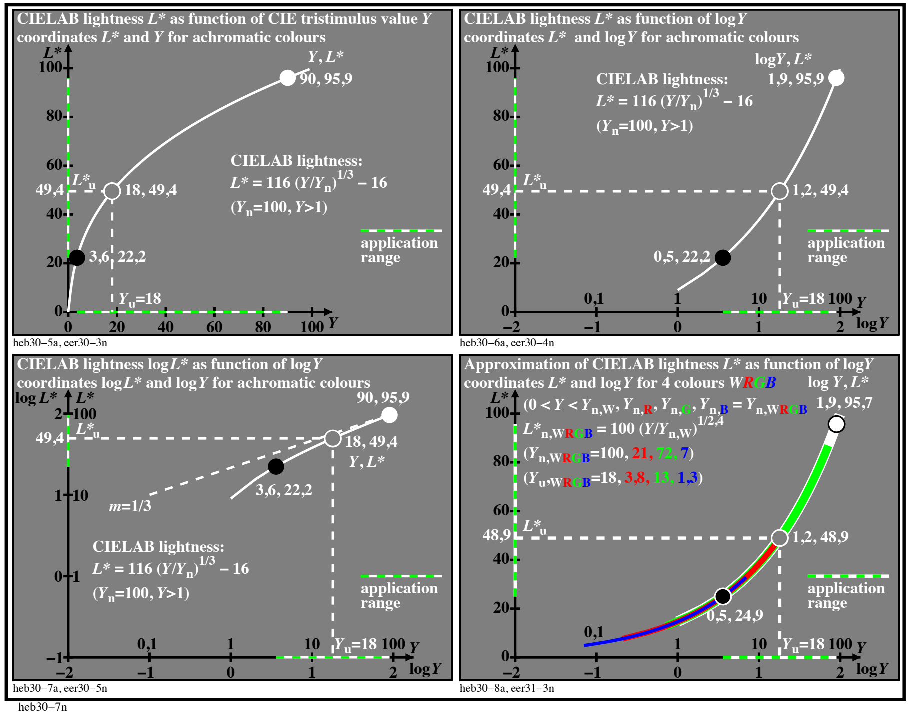


Figure 9: Lightness *L^*_{CIELAB}* and tristimulus value *Y* on linear and logarithmic axes

To download this image, see http://color.li.tu-berlin.de/heb3/heb30-7n.pdf

Figure 9 contains four separate images with linear and logarithmic coordinates on the *x* and *y* axes. Of particular colourimetric interest is the output log L^*_{CIELAB} as a function of log *Y* at the bottom left. The slope is 1/3 for white W (Y_{w}=90) and 1/2,4 for medium grey U (Y_{u}=18). The slope 1/2,4 is used in IEC 61966-2-1 (*sRGB* colour space) to define the lightness T^*_{IECsRGB}. The figures above and below right show L^*_{CIELAB} for the four display colours W and sRGB.

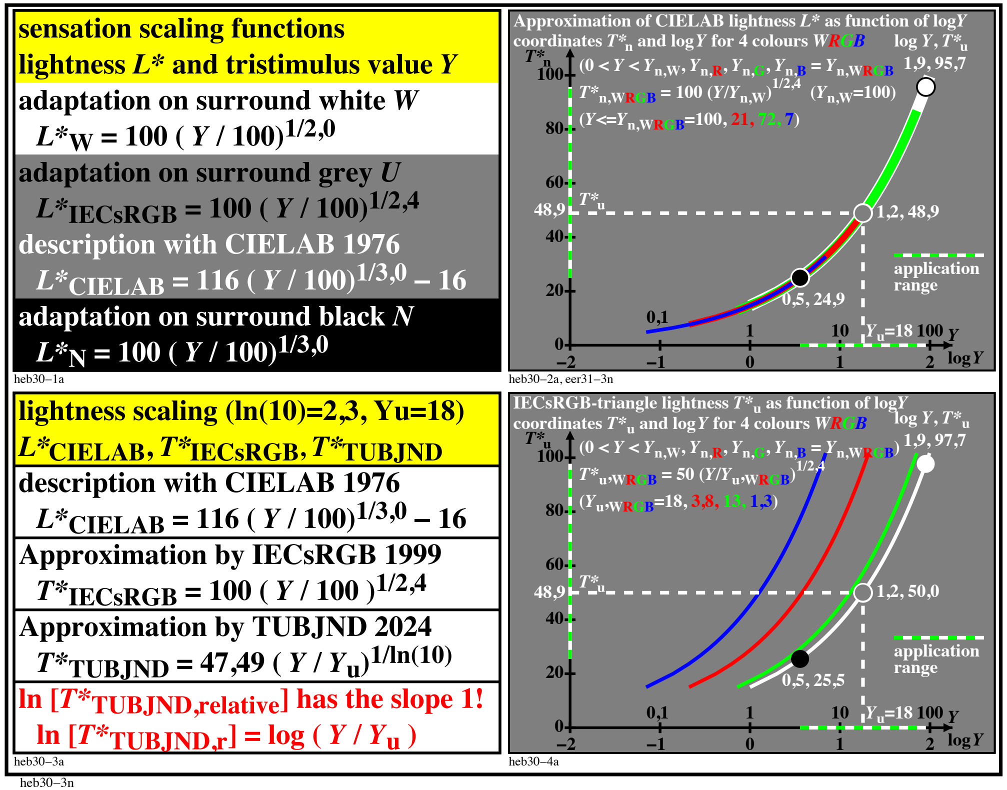


Figure 10: Comparison of the lightness values L^*_{CIELAB}, $T^*_{IECsRGBn}$, and $T^*_{TUBJNDu}$

To download this image, see http://color.li.tu-berlin.de/heb3/heb30-3n.pdf

The lightness L^*_{CIELAB} is calculated from the *relative* lightness values Y/Y_n with Y_n=100 for white and the exponent 1/3. The lightnesses $T^*_{IECsRGBn}$ and $T^*_{TUBJNDu}$ use the *relative* tristimulus values Y/Y_{sRGB} and an exponent close to 1/2,4. If you use the *natural* logarithm **ln** instead of **log** in Figure 9 (bottom left), the **slope is 1 because of ln** a = ln(10) **log** a = 2.30 **log** a. This results in the following equation for lightness: $T^*_{TUBJNDr} = e^{(Xr)}$ with $x_r = (Y / Y_u)$. This applies to a wide range from black N to white W around medium grey U with Y_u=18.

5. Visual interval scaling and equidistant 9-step grey output with inverse data

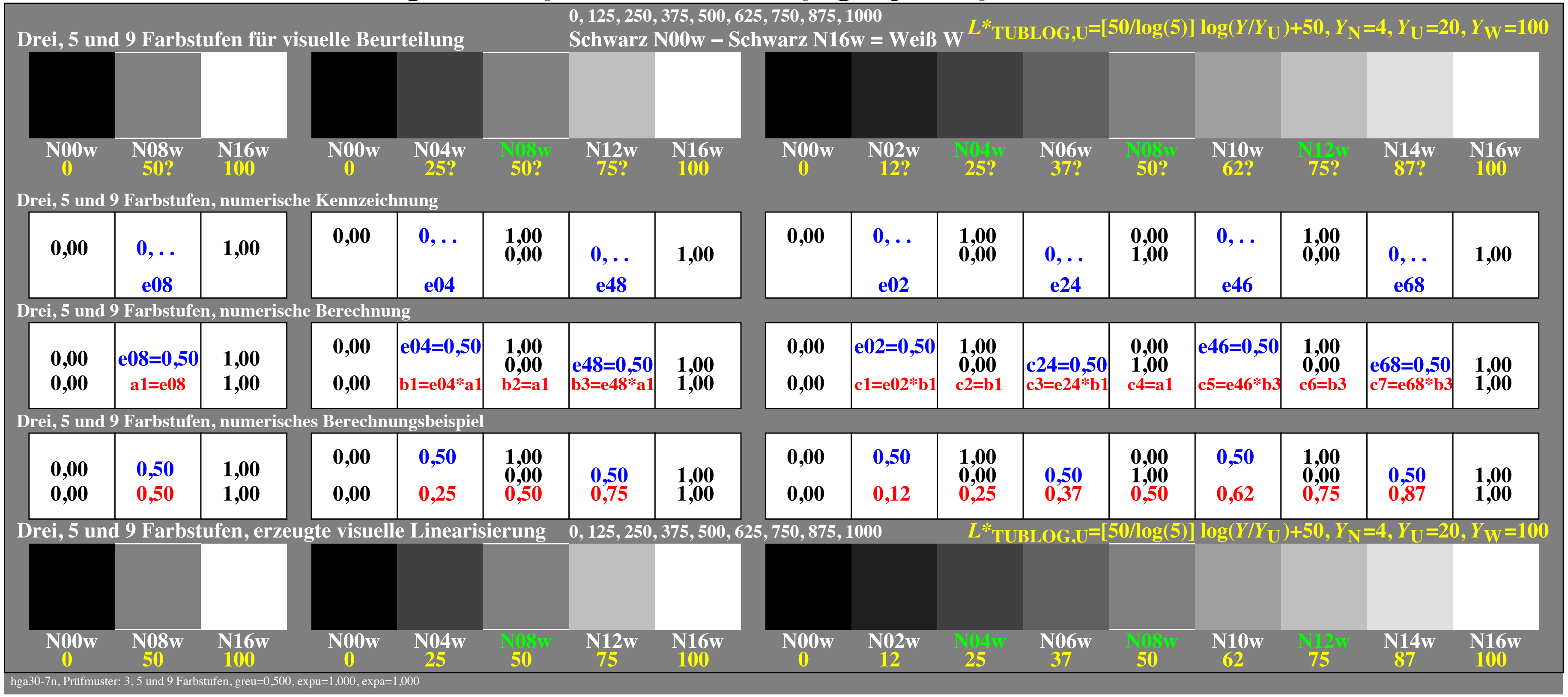


Figure 11: Three, 5 and 9-step grey scales: interval scaling and equidistant output

To download this image, see http://color.li.tu-berlin.de/hea3/hea30-7n.pdf

Vision research is faced with the scaling of lightness within a wide luminance range from peak black p2 to peak white P2. Figure 11 uses visual interval scaling between adjacent grey scales. It is assumed, that the equally spaced file data 0 <= *rgb** <=1 according to ISO 9241-306 generate the luminance range between p2 and P2 according to ISO 22028-5. Then the luminance range has increased by a factor of 25 compared to the luminance range of SDR (N-W).

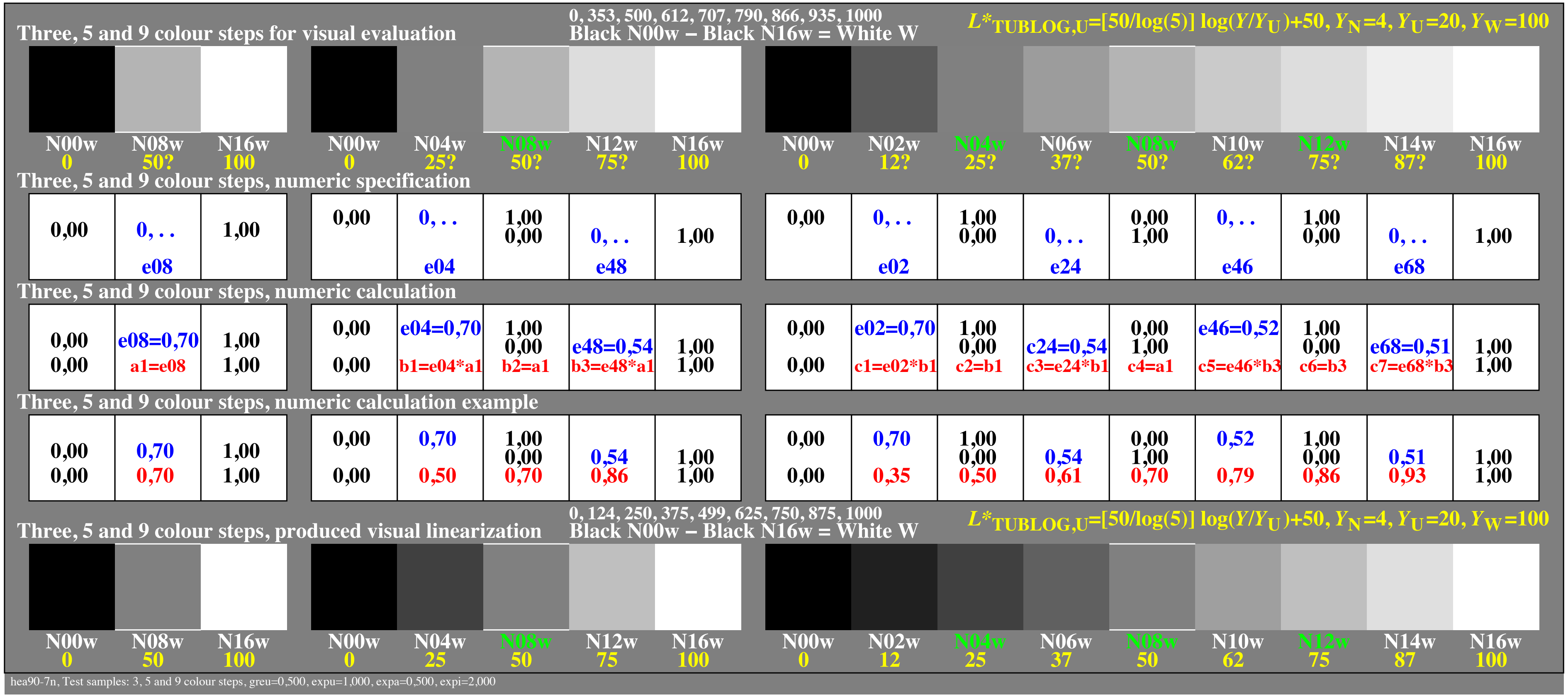


Figure 12: Three, 5 and 9-level grey scales: interval scaling and equidistant output

To download this image, see http://color.li.tu-berlin.de/hea9/hea90-7n.pdf

Compared to Figure 11, Figure 12 shows large differences in lightness close to Black N. Accordingly, the visual interval scaling results in a large value e02=0,70 close to Black N. The software uses the visual values exy (blue) to produce a visually spaced output (bottom row). The programming language *PostScript* is used to change the *rgb** values in the file. This change is based on 7 values c1 to c7 (red), which are calculated in the Figure 12 from the 7 values exy (blue).

6. Equidistant 9-step colour output (1080 colours, ISO 9241-306) with inverse data

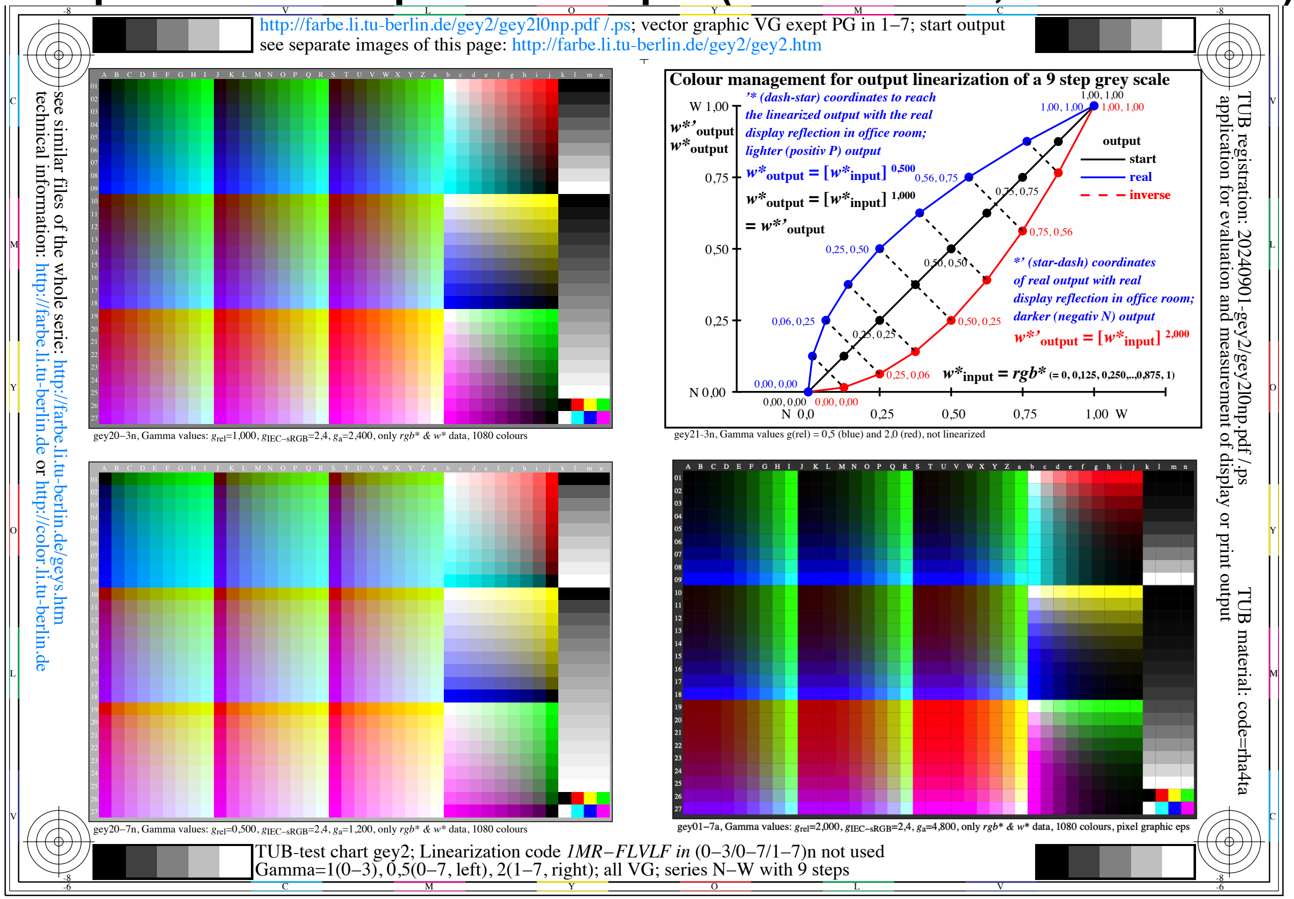


Figure 13: Three different outputs of 1080 colours according to ISO 9241-306 and in-output

To download this image, see http://color.li.tu-berlin.de/gey2/gey2l0np.pdf

Figure 13 shows three outputs of the 1080 colours according to ISO 9241-306. The output in the upper left shows an equidistant output on most displays. In the lower left, the greyscale in the dark area is too large and in the lower right is too small. At top right, the in-output for 9 steps is shown.

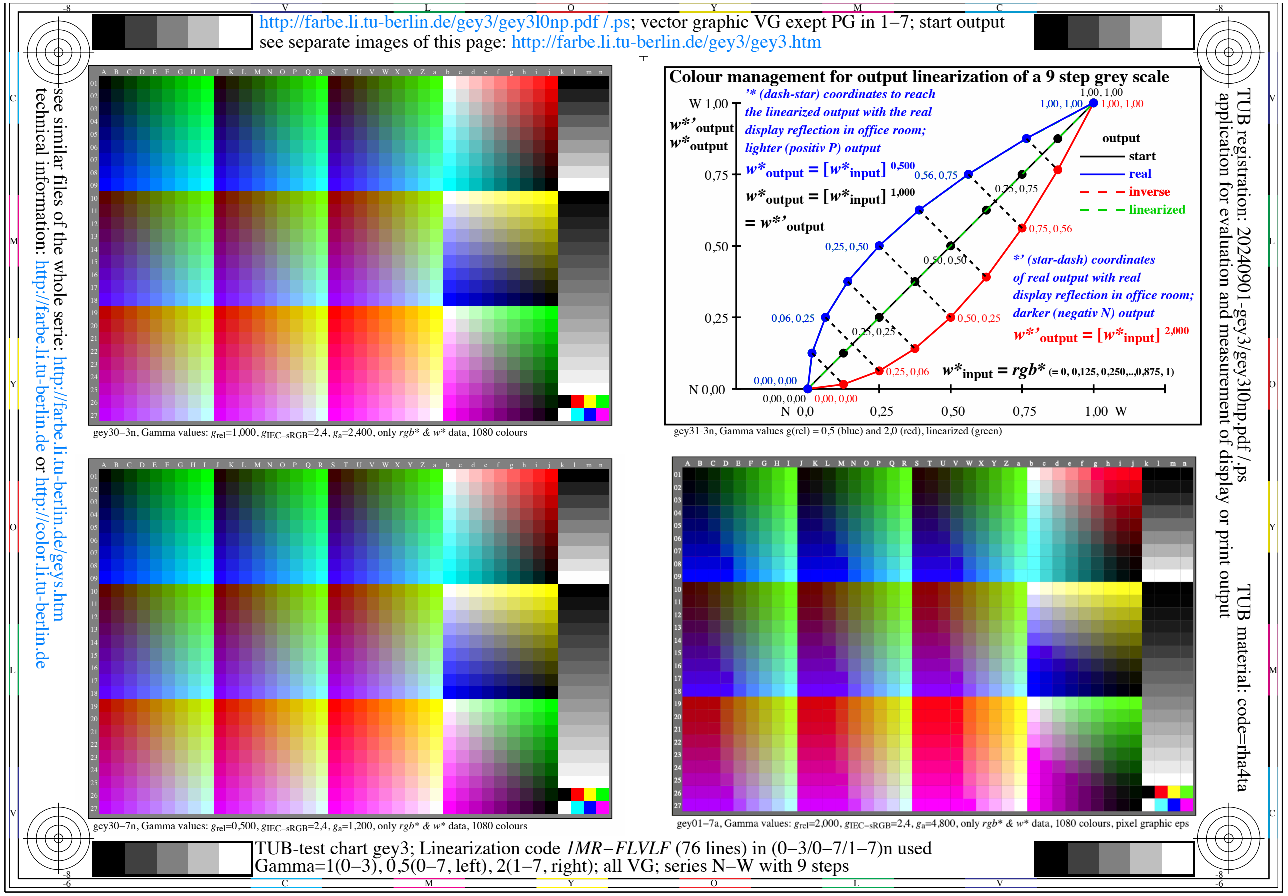


Figure 14: Three equal outputs of the 1080 colours according to ISO 9241-306 and in-output

To download this image, see http://color.li.tu-berlin.de/gey3/gey3l0np.pdf

Visual interval scaling and the *PostScript* programming language are used to change the *rgb** values. All three images show an almost visually equidistant output.

The output of the modified image is fast. Vector and pixel graphics take about 1s. The software *GraphicConverter* was used to convert the file formats ***pdf*** to ***eps*** and back.

7. Discussion of the results with a model to describe the colour appearance

The colourimetric capture of the luminance and chromaticity of the original is a main goal of photography. As a rule, a *relative* colourimetric rendering of the luminance is sufficient.

Another main goal is *the same relative spacing* compared to the original. Otherwise, important information is missing. For the description of the *image quality* the *regularity index g** according to ISO/IEC 15775, Annex G, is used.

In this paper, the S-shaped receptor-excitation function $F_{ab}(x_r)$ is used as the basis for the TUB colour-vision model. The derivation $F_{ab}(x_r)/dx$ of the physiological S-shaped excitation function $F_{ab}(x_r)$ produces the luminance contrast ($L/\Delta L$). The integration of ($L/\Delta L$) dx again generates the excitation function $F_{ab}(x_r)$, see figures 1 to 3.

Chapters 4 to 6 contain new research results. For example, approximately, compare $\boldsymbol{F_{ab}(x_r)}$

$\mathbf{log\ [}\boldsymbol{L^*}_{\mathbf{CIELAB}}\mathbf{\ /\ }\boldsymbol{L^*}_{\mathbf{CIELABu}}\mathbf{]=1/ln(10)}\ \boldsymbol{x_r},\qquad \boldsymbol{x_r}\mathbf{=log\ (}\boldsymbol{Y/Y_u}\mathbf{)=log\ (}\boldsymbol{L/L_u}\mathbf{)}$ (Y_u=18, L_u=28 cd/m^2)

or with the relative (r) lightness normalized to the environment U $\boldsymbol{L^*}_{\mathbf{CIELABr}} = \boldsymbol{L^*}_{\mathbf{CIELAB}} / \boldsymbol{L^*}_{\mathbf{CIELABu}}$,

$\mathbf{ln\ [}\boldsymbol{L^*}_{\mathbf{CIELABr}}\mathbf{]=}\boldsymbol{x_r}.$ log a = ln(a) / ln(10), L^*_{CIELABu} = 50 for Yu = 18 and ln(10)=2,3

or

$\boldsymbol{L^*}_{\mathbf{CIELABr}} = \mathbf{e}^{\boldsymbol{x_r}}$

With the physiological complementary excitation $\mathbf{e}^{-\boldsymbol{x_r}}$, the colour appearance is

$\boldsymbol{L^{**}}_{\mathbf{CIELABr}} = (\mathbf{e}^{\boldsymbol{x_r}} - \mathbf{e}^{-\boldsymbol{x_r}}) / (\mathbf{e}^{\boldsymbol{x_r}} + \mathbf{e}^{-\boldsymbol{x_r}})$

Result: The **headroom** between the diffuse white W and peak white P2 is approx. 72% corresponding to the line $\boldsymbol{L^*}_{\mathbf{CIELABr}}$, and approx. 15% corresponding to the hyperbolic function $\boldsymbol{L^{**}}_{\mathbf{CIELABr}}$.
New software generates 9-step equally spaced grey series and probably yields about 15%.
ISO 22028-5:2023 uses 72% for the HDR head room and 100/1,72% = 58% for the SDR room.

8. Literature

[1] ISO 9241-306:2018, Ergonomics of human-system interaction - Part 306: On-site evaluation methods for electronic optical displays, see to download the test charts with user questions for ther ergonomic output on displays, https://standards.iso.org/iso/9241/306/ed-2/index.html

[2] ISO/IEC 15775/ed-2:2022, Information technology - Office and data technology - Method for marking the image reproduction of colour copiers and multifunction devices with copying functions by printed test charts, see for downloading the test charts with user questions for sustainable copiers. The test charts of [1] and [2] are similar, see https://standards.iso.org/iso-iec/15775/ed-2/en

[3] ISO/TS 22028-5:2023 Photography and Graphic Technology - Extended Colour Gamuts for Storage, Editing, and Exchange of Digital Images - Part 5: High Dynamic Range and Wide Colour Space Encoding for Still Image (HDR/WCG)

[4] Richter, Klaus (2013), Output Linearization Methods for Displays, Printers and Offset Printing (63 pages, 1,4 MB, A4 format), see http://color.li.tu-berlin.de/OUTLIN13_02.PDF

[5] CIE 15, Farbmetrik

[6] IEC 61966-2-1, Multimedia Systems and Devices - Colour Measurement and Management - Part 2-1: Colour Management - Standard RGB Colour Space - sRGB.

[7] ISO 8995-1:2002 Lighting at the workplace – Part 1: Interior

[8] *Richter, Klaus (2019),* Colourimetric scanning, displaying and printing for archiving based on the ergonomic international standard ISO 9241-306:2018 at workplaces**,** *Proc. IS&T Archiving 2019*, pp.

111-112, see for free *pdf* download
https://doi.org/10.2352/issn.2168-3204.2019.1.0.25

[9] *Richter, Klaus (2024),* see various works, especially since 2020 at the link
http://color.li.tu-berlin.de/XY91FEN.html

[10] DIN 33872-1 to 6:2010, Information technology - Office and data technology - Method for marking relative colour rendering with YES/NO criteria -
Part 1: Classification, terms and basics, only on CD-ROM,
Part 2 to 6: Test files for output properties,
Part 2: Examination of the distinctiveness of the 5- and 16-step colour series,
Part 3: Examination of equality for four equivalent grey definitions and distinguishability of the 16 steps of grey,
Part 4: Testing equality for two equivalent colour definitions with 5 and 16 step colour series,
Part 5: Testing of elementary colour correspondence and hue discrimination,
Part 6: Testting of the equivalent spacing and the regular chromatic spacing,
see to download test charts http://color.li.tu-berlin.de/A/33872.html

[11] *Richter, Klaus* (2024) Frame File Colour Management (FF_CM) for ergonomic display output of SDR and HDR-rgb* images on SDR and HDR displays, see for free *pdf* download
http://color.li.tu-berlin.de/disgam25e.pdf

[12] *Richter, Klaus* (2024) Colourimetric reproduction of luminance and chromaticity of *rgb** images on SDR and HDR displays by a TUB colour-vision model, see for free *pdf* download
http://color.li.tu-berlin.de/dislum25e.pdf

[13] *Richter, Klaus* (1996), Computer graphics and colourimetry – colour systems, *PostScript* and device-independent CIE colours, 228 pages, see at least figures on scaling and response functions on pages 104 to 127, see (8,7 MB)
http://color.li.tu-berlin.de/BUCHAF.PDF

Appendix – Copyright

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