

# Recent work on the Helmholtz-Kohlrausch effect

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# Introduction



**Gregory High** PhD

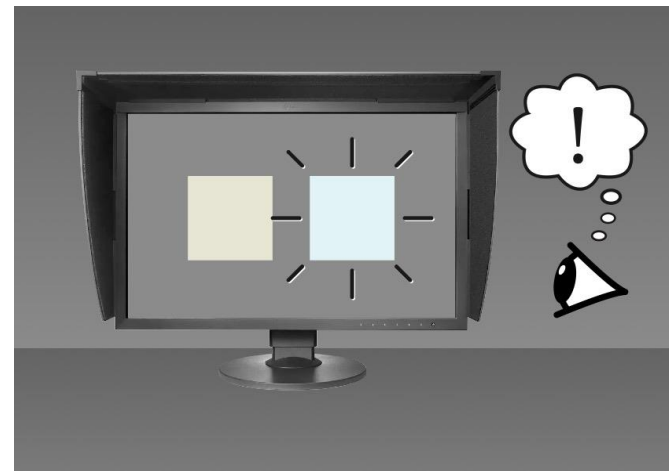
- Background in graphic arts
- Completed PhD at NTNU Colourlab in 2024
- Research areas included:
  - Consistent colour appearance
  - Grey balance
  - Helmholtz-Kohlrausch effect
  - Visual difference between colour reproductions

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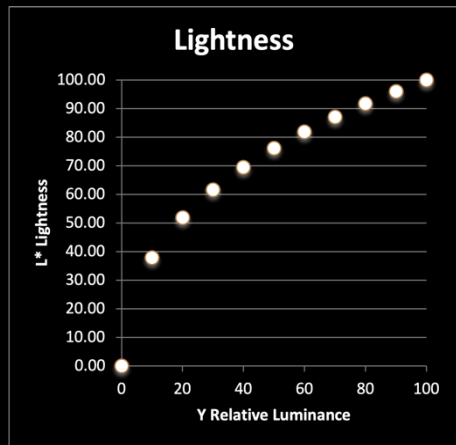
# Original motivation

- Soft proof display-based comparisons of simulated prints
- Some substrates look brighter than others, even if when are of equal luminance
- The **SDR** display's gamut does not allow some substrates (high in OBAs) to be displayed accurately
- Needs an **HDR** approach to render multiple different near-white paper colours



# Achromatic lightness

- Hard to judge individual luminances
- Relative brightness  $\approx$  lightness



$$L^* = 116(Y/Y_n)^{1/3} - 16$$

100  
cd/m<sup>2</sup>



$L^* = 100$

50 cd/m<sup>2</sup>



$L^* = 75$

20 cd/m<sup>2</sup>



$L^* = 50$

5 cd/m<sup>2</sup>



$L^* = 25$

0 cd/m<sup>2</sup>



$L^* = 0$

← Lightness relative  
to an adapting  
whitepoint or  
diffuse whitepoint

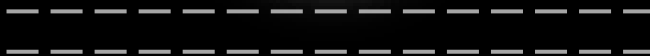
*Colorimetrically, two  
patches of equal  
luminance also have  
equal  $L^*$  lightness!*

# Brightness

200  
 $\text{cd/m}^2$



Luminous colour



Fluorence

# Lightness

100  
 $\text{cd/m}^2$



$L^* = 100$



Adapting / diffuse  
whitepoint

50  $\text{cd/m}^2$



$L^* = 75$

20  $\text{cd/m}^2$



$L^* = 50$



Non-luminous  
colour

5  $\text{cd/m}^2$



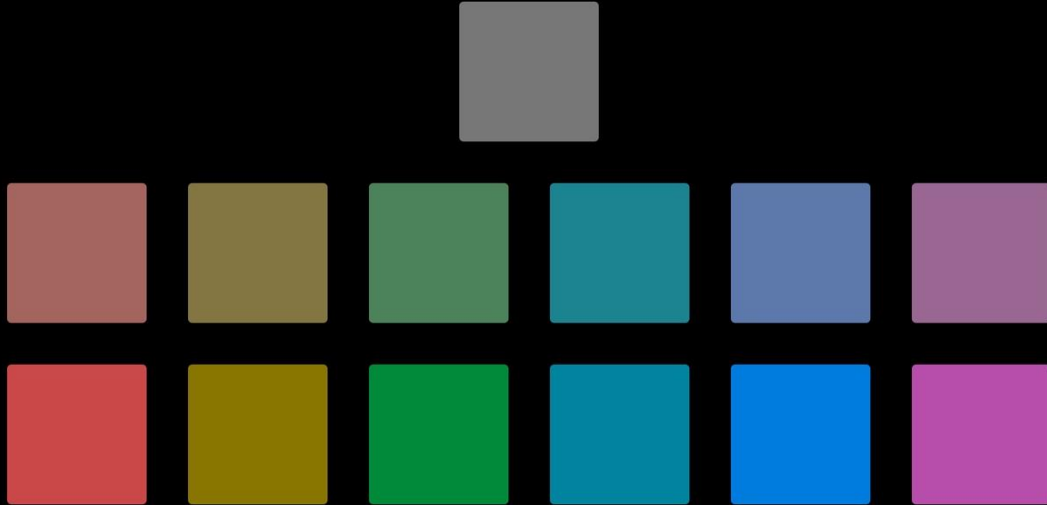
$L^* = 25$

0  $\text{cd/m}^2$



$L^* = 0$

# The Helmsoltz-Kohlrausch Effect



Colours are of equal luminances,  
but appear to have different brightnesses

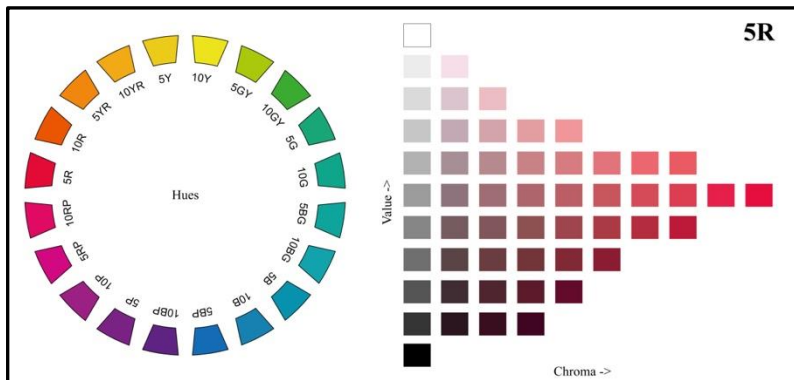
# Helmholtz on luminosity

- “ I scarcely trust my judgement upon the equivalence of the heterochromatic brightnesses, at any rate upon greater and smaller in extreme cases...
- “ As far as my own senses are concerned I have the impression that in heterochromatic luminosity equations it is not a question of the comparison on one magnitude, but the combination of two, brightness and colour-glow (*farbengluth*), for which I do not know how to form any simple sum, and which too I cannot further define in scientific terms.”

Hermann von Helmholtz

In Parsons, J.H., 1924. *An Introduction to the study of colour vision* 2nd ed., Cambridge University Press.

# H-K effect in colour order systems (and uniform colour spaces)



## Munsell System

Shows the three-dimensional relationships between:

- Munsell Hue
- Munsell Value (lightness)
- Munsell Chroma

*but...*

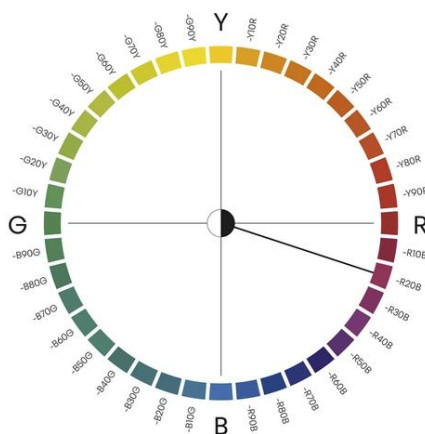
Patches with equal Munsell Values (lightness) are of roughly equal luminance reflectance. Therefore, Munsell Values do not include contribution of H-K effect to lightness/brightness

Munsell-based data often used to test uniform colour spaces

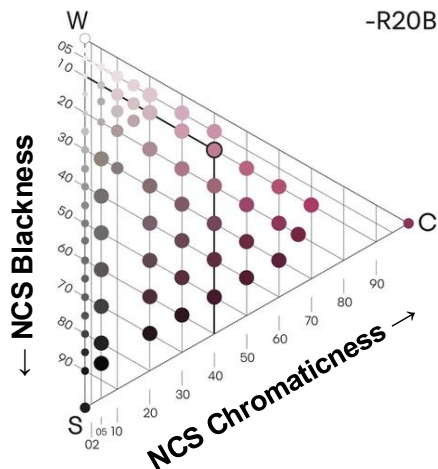


Image: Billmeyer and Saltzman (2001)

# HK effect included in some colour order systems



1. Find the colour hue: -R20B



2. Find the nuance: 1040

NCS S 1040-R20B

Blackness (s)      Chromaticity (c)      Hue

s      c      Hue



3. Complete the NCS Notation

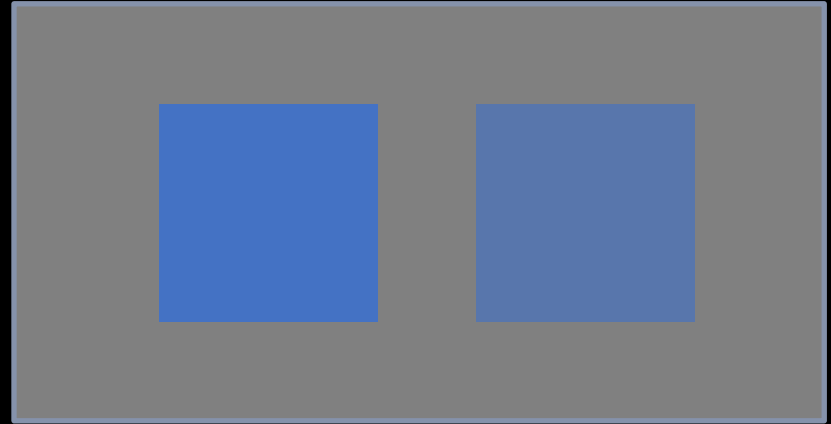
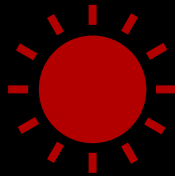
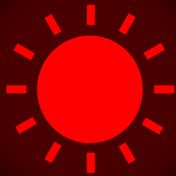
## NCS Colour System

Blackness (s) + Chromaticity (c) + Whiteness (w) = 100

Appearance approach includes contribution of the HK effect

Image: [www.ncscolour.com](http://www.ncscolour.com)

# Why is H-K Effect difficult to quantify?

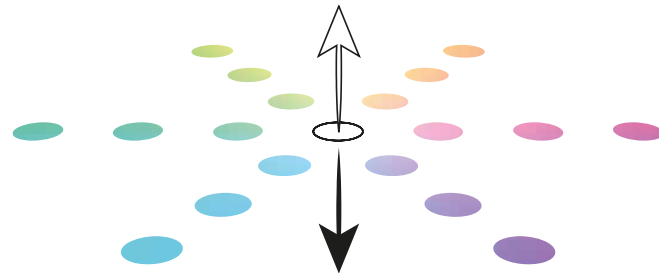


- Brightness and Lightness matching tasks (including display-based) give very noisy observer data
- Experiments with physical samples ( but more limited gamut) provide better / lower variability

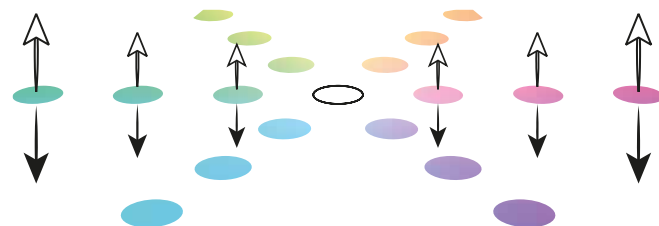
# Methods of adjustment for Matching Lightness

Nayatani<sup>1</sup> compares two lightness matching methods:  
VAC & VCC

- VAC reports a weaker H-K effect, but with less variability
- VCC reports a stronger H-K effect but with greater variability (task is more difficult for observers)



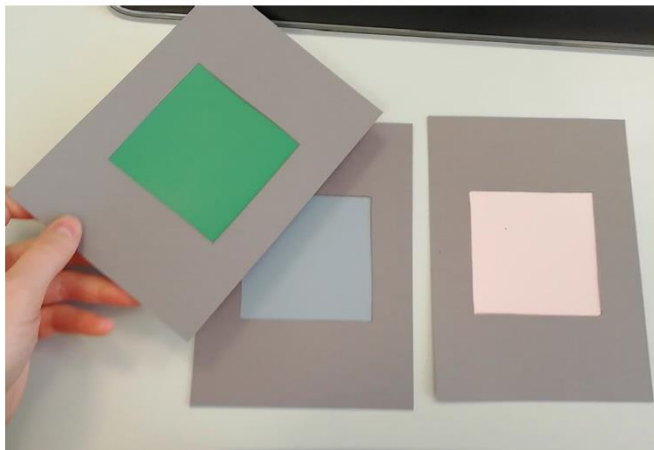
Method of Variable-Achromatic-Color (VAC)



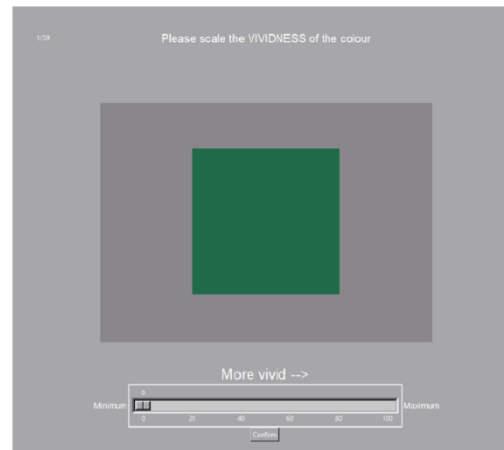
Method of Variable-Chromatic-Color (VCC)

[1] Nayatani, Y., 1997. *Simple estimation methods for the Helmholtz–Kohlrausch effect*. *Color Research & Application*, 22(6), pp.385–401.

# Viewing modes and cognitive effects



- Physical samples in viewing booth



- Identical colour patches on a colour managed display

## Example:

Observers estimate vividness with physical samples and on-screen.

Despite carefully matched viewing conditions and protocols (room, surround, background, etc.), samples were estimated to be less vivid on the display

Midtjord, Helene B., Phil Green, and Peter Nussbaum. 'Vividness as a Colour Appearance Attribute'. *Proc. IS&T 27th Color and Imaging Conference 27* (October 2019): 308–13

# Hunter's modes of colour appearance

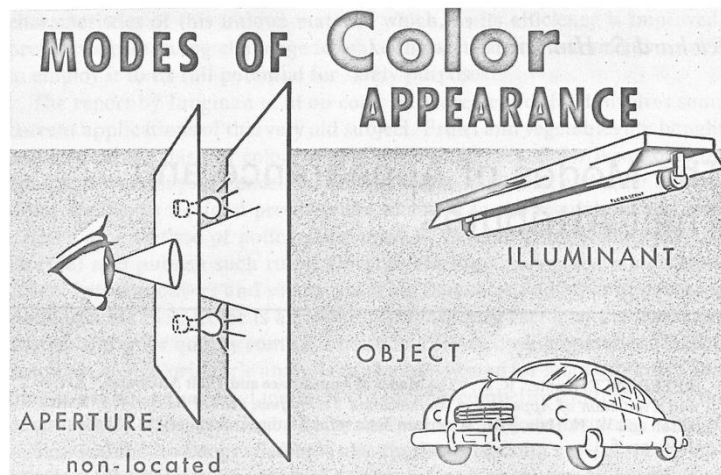


FIG. 1—The three modes of color appearance.

Hunter, Richard S. The modes of appearance and their attributes.  
*Review and evaluation of appearance: methods and techniques.* ASTM  
 International, 1986.

1. **Aperture:** The color is seen through a hole so that the observer is unable to identify the illuminant or objects involved or both. He can measure only the distribution of energy passing through the aperture.
2. **Illuminant:** For lights and other self-luminous objects. Spectral and geometric distributions of light can be measured.
3. **Object:** The observer is conscious of both the object seen and its environment.

Hunter follows Judd's classification of optical attributes, which became an ASTM standard in 1961, and the terminology has remained largely unchanged.

- ASTM E284-17 *Standard Terminology of Appearance*. ASTM International; 2017.

# Why is H-K Effect difficult to quantify?

Systematic causes of discrepancies include:

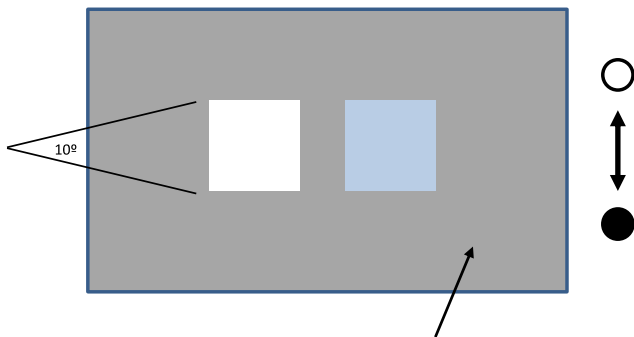
- Viewing mode
- Simultaneous contrast with background
- Field size and viewing angle

## H-K often excluded from UCSs & CAMs

These factors are difficult to introduce into UCSs & CAMs, so the H-K effect is typically excluded for related-colours, since the calculations add complexity and are not easily invertible.

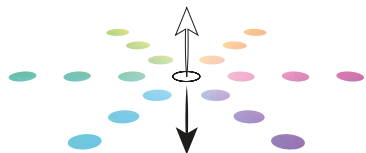
# Our experiments (2021 & 2023)

## HK effect in light colours

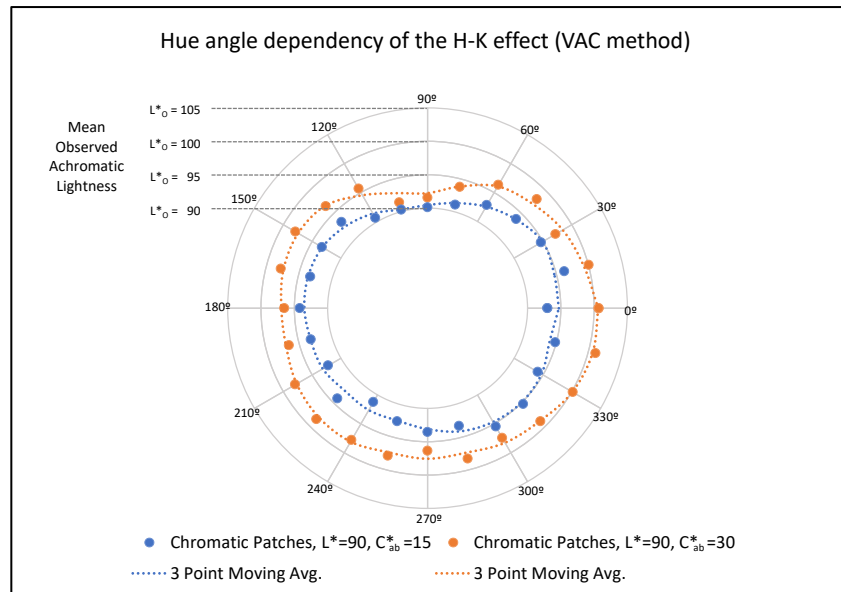


Full-screen grey surround, with a luminance factor of 0.2 relative to the inferred 120cd/m<sup>2</sup> white point.

Soft proofing P2 viewing condition with dim room lighting (ISO 3664)



Method of Variable-Achromatic-Color (VAC)



- Display-based experiment using colour test patches of all hues at 15° intervals.
- All test patches @  $L^*$  of 90, but observed lightness as high as  $L^*$  of 100.
- Note the blue/yellow and red/green opponency.

# Hue dependency – Bi-modal distribution?

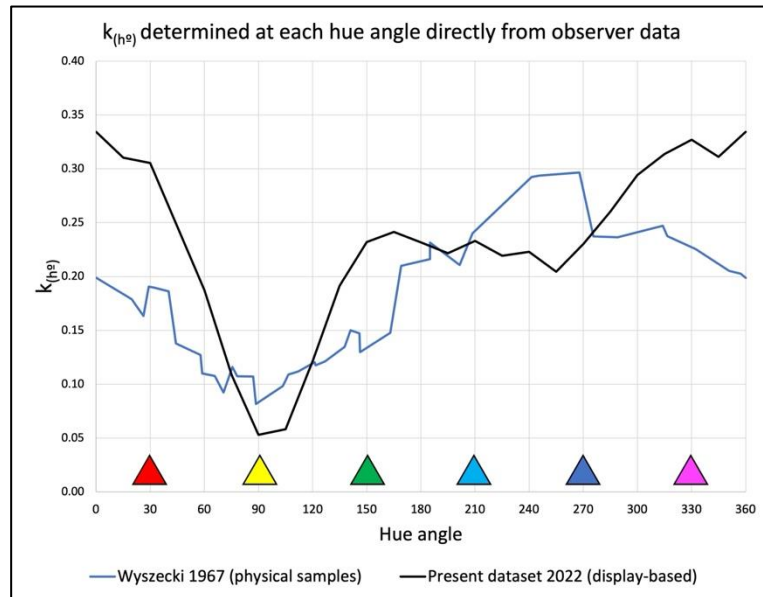
Inconsistent results between experiments in object mode and aperture mode

## Wyszecki (1967)

- Data set from matching physical samples to a Munsell neutral scale
- HK weakest in yellows, strongest in blues

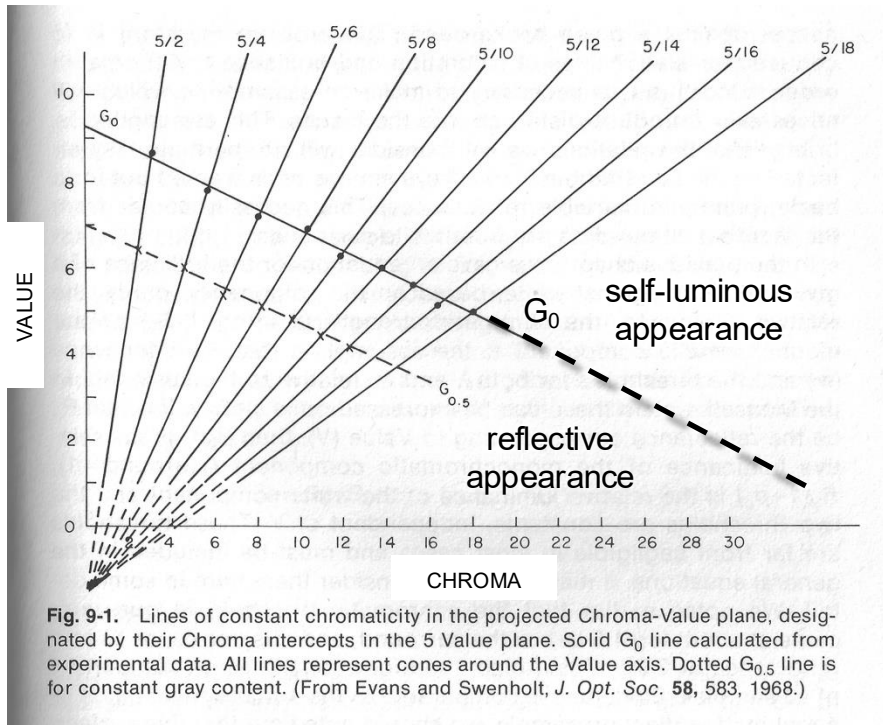
## High et al (2023)

- Display-based VAC method of adjustment
- Additional peak in reds/magentas



$K(h^\circ)$  is a constant describing the increase in perceived lightness (due to H-K) relative to chroma for each hue angle

# H-K hue dependency on HDR display



## Xie and Fairchild (2021)

- Uses Ralph Evans' concept of zero greyness ( $G_0$ ) (Similar concept to NCS Blackness of zero)
- Can determine the boundary between reflective and self-luminous stimulus appearance
- Includes the H-K Effect
- On an WCG HDR, the H-K Effect peaked in red hues

Xie, Hao, and Mark D. Fairchild. 'G0 Revisited as Equally Bright Reference Boundary'. *29th Color and Imaging Conference 2021*, no. 1 (2021): 247–52. <https://doi.org/10.2352/jissn.2169-2629.2021.29.247>.

# Modelling: how to include HK in colorimetry

A typical strategy for HK-adjusted lightness:

- Add some fraction of colourfulness to the achromatic intensity (or a fraction of sample's Chroma to its Lightness)

$$L_{EAL}^* = L^* + k \cdot C_{ab}^*$$

*where  $L^*$  and  $C_{ab}^*$  are the colorimetric values of a sample,  $k$  is a constant (some factor of  $C_{ab}^*$ ), and  $L_{EAL}^*$  is the predicted equivalent achromatic lightness.*

However;

- Does not address the reported hue-angle dependency
- Relies on assumption of uniformity for the colourspace

# Modified colour models

## Fairchild & Pirrotta (1991)

- Modified CIELAB  $L^*$
- Fitted the Wyszecki (object mode) data with a  $\frac{1}{2}$  sine function (scaling factor for lightnesses between blue and yellow hues)

Fairchild, Mark D., and Elizabeth Pirrotta. 'Predicting the Lightness of Chromatic Object Colors Using CIELAB'. Color Research & Application 16, no. 6 (1991): 385–93. <https://doi.org/10.1002/col.5080160608>.

$$L_{\text{EAL}}^* = L^* + f_{BY}(h^\circ) \cdot C_{ab}^* \quad f_{BY}(h^\circ) = k_1 \cdot \left| \sin \left( \frac{h^\circ - 90}{2} \right) \right| + k_2$$

## High, Nussbaum & Green (2023)

- Extended the 1991 model with an additional term for red hues

High, Gregory, Phil Green, and Peter Nussbaum. 'The Helmholtz-Kohlrausch Effect on Display-Based Light Colors and Simulated Substrate Colors'. Color Research & Application 48, no. 2 (2023): 167–77. <https://doi.org/10.1002/col.22839>.

$$L_{\text{EAL}}^* = L^* + (f_{BY}(h^\circ) + f_R(h^\circ)) \cdot C_{ab}^* \quad f_R(h^\circ) = \begin{cases} k_3 \cdot |\cos(h^\circ)| + k_4, & \text{for } -90^\circ \leq h^\circ \leq 90^\circ \\ 0, & \text{otherwise.} \end{cases}$$

# Modified appearance models

Hellwig et al. (2022/2023/2024)

- Avoided method of adjustment (used pair comparison instead)
- Modified version of CAM16
- Amended hue-dependent chromatic strength eccentricity function ( $e_t$ ) addresses non uniformities in CAM16-UCS

$$J_{HK} = \sqrt{J^2 + 66C}$$

- Modification of UCS accounts for much of the H-K hue dependence

***Questions remain about the flat yellow response and differences in appearance modes***

Hellwig, Luke, Dale Stoltzka, and Mark D. Fairchild. 'Extending CIECAM02 and CAM16 for the Helmholtz-Kohlrausch Effect'. *Color Research & Application* 47, no. 5 (2022): 1096–104. <https://doi.org/10.1002/col.22793>.

Hellwig, Luke, and Mark D. Fairchild. 'Brightness, Lightness, Colorfulness, and Chroma in CIECAM02 and CAM16'. *Color Research & Application* 47, no. 5 (2022): 1–13. <https://doi.org/10.1002/col.22792>.

Hellwig, Luke, Dale Stoltzka, and Mark D. Fairchild. 'The Brightness of Chromatic Stimuli'. *Color Research & Application* 49, no. 1 (2024): 113–23. <https://doi.org/10.1002/col.22910>.

# More recent works

## *Lightness Modifications of the CIECAM16 and CIELAB based on the Helmholtz-Kohlrausch Effect*

Liao and Xu (2024)

- Display based
- Confirms peak in red colours, but limited to light red colours
- Alternative models for CAM16 and CIELAB
- Construction of lookup table LUT for future applications

Liao, Zhihui, and Lihao Xu. 'Lightness Modifications of the CIECAM16 and CIELAB Based on the Helmholtz-Kohlrausch Effect'. Optics Express 32, no. 25 (2024): 44918–32.  
<https://doi.org/10.1364/OE.534073>.

# More recent works

## *An Investigation Into the Bimodal Hue Dependency of the Helmholtz-Kohlrausch Effect*

Li, Xu and Luo (2026)

- Confirms bi-modal nature (red and blue peaks in H-K effect), especially for high luminance and highly saturated stimuli
- Supports Hellwig's modified CAM16 eccentricity function

Li, Molin, Lihao Xu, and Ming Ronnier Luo. 'An Investigation Into the Bimodal Hue Dependency of the Helmholtz–Kohlrausch Effect'. *Color Research & Application* 51, no. 2 (2026): e70057. <https://doi.org/10.1002/col.70057>.

# More recent works

## *Fundamental Lightness and Brightness Scales*

Abasi and Fairchild (2025)

- One dimensional Fundamental Lightness and Brightness Scales (FLS and FBS)
- Lightness is normalised relative to  $G_0$  of a colour's chromaticity
- Calculated in LMS cone-space (avoids colorimetry)

Abasi, Saeedeh, and Mark D. Fairchild. 'Fundamental Lightness and Brightness Scales'. Optics Express 33, no. 21 (2025): 44405–21. <https://doi.org/10.1364/OE.571753>.

# Lightness, brightness and H-K in HDR



© Jesse Dimick 2024

- Surface colours, specular highlights and direct light sources at point of capture
- Rendered for viewing on display
- Breaks the traditional boundaries between modes of colour appearance
- Implications for HDR and SDR tone and gamut mapping (for example, retaining relative brightness between visual elements)

# Thank you for your attention

## Contact information:

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