Colour vision and visual performance in the mesopic range

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Farbensehen und Sehleistung im Dämmerungssehen

Summary-1

- Aim:
  - predict mesopic detection contrast thresholds
  - for spectral increments on a fixed mesopic background
- Predicting quantity: *C*
  - contrast type
  - includes both achromatic and chromatic terms → not a luminance type descriptor
    - (not a photometric quantity)

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Summary-2

- The detection threshold is at *C*=1
- From this criterion, a spectral non-additivity formula is derived
- It is called **NA-formula**
- for a mesopic **luminance difference type** quantity
  - predicting the non-additivity of „mesopic contrast” at or around the detection threshold
  - actual values of NA are computed for realistic examples (NA~10%-30%)

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Models of mesopic vision-1

- Rod-cone and cone-cone interactions
- *V*(λ) is not usable to predict visual performance in the mesopic range
- Mesopic brightness models are not usable either
  - heterochromatic brightness matching: steady above-threshold stimuli
  - mesopic visual performance (detection, recognition, or reaction time) models have a different form
    - the visual system usually operates at or near threshold

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Models of mesopic vision-2

- Current *models* of mesopic visual performance are *photometric* models
  - spectral integration → spectral *additivity*
  - linear combination of V(λ) and V’(λ)
  - “chromatic” model→“**multi-peak**” behaviour of the **spectral** sensitivity curve
  - reason: influence of chromatic (opponent) channels

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Spectral additivity-1

- Definition of spectral additivity of any mathematical descriptor *C* of a perceived quantity (e.g. detection threshold)
- The descriptor *C* of a psychometrically determined stimulus S of any composite spectral power distribution can be predicted accurately by summing up the *C* values corresponding to the stimuli of the constituent spectral power distributions of S.

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Spectral additivity-2

- A good mathematical descriptor of mesopic visual performance is *not always additive*
  - we can prove this *non-additivity statement* mathematically (see the manuscript)
  - example: a contrast-type descriptor of mesopic detection thresholds (C)
  - *C* is based on
    - the result of our recent psycho-physical experiment
    - and a mesopic visual performance model from literature
    - a non-additivity (NA) formula can also be derived for a luminance-type metric related to *C*

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Spectral additivity-3

- Mesopic luminance itself (of standalone above-threshold stimuli) has already been pointed out to be non-additive due to its definition by an integral equation (Sam Berman).
- But this work deals with the detection threshold of light increments projected on a fixed mesopic background.
- A contrast-type quantity (C) at or around threshold is more relevant to characterize mesopic visual performance than mesopic luminance itself.

Additivity of mesopic contrast on a fixed background-1

- If the light increment on the background is at or around the detection threshold then we can assume that the level of mesopic adaptation does not change if the light increment changes spectrally
- In this special case of increment thresholds, a **luminance** contrast type quantity is **spectrally additive**
  - see the manuscript for mathematical evidence
    - ...of course this is not equivalent of saying that this **luminance** contrast type quantity is a good descriptor...

Additivity of mesopic contrast on a fixed background-2

- For accurate description of off-axis mesopic detection thresholds:
- An advanced (non-photometric) contrast formula (*C*-formula) shall be used
  - including cone signal *difference terms*
  - similar to the descriptors of colour appearance
  - to include the opponent retinal mechanisms
  - such difference terms result in spectral non-additivity of a corresponding luminance contrast type quantity
    - mathematical evidence is described in the manuscript

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Modelling mesopic contrast

- $C = a_1 \Delta Y + a_2 \Delta Y' + a_3 \Delta S + a_4 \,|\, \Delta L - 1.25\, \Delta M \,|$

→C=1 at the detection threshold

→ In lighting practice, we can compute the amount of irradiance necessary for object detection from C=1,

→ if the spectral reflectance of the target (e.g. a yellow life vest) and the background (e.g. asphalt) and the relative SPD (i.e. the type, e.g. white phosphor LED) of the light source illuminating the road are given.

$\Delta Y = \int V(\lambda)\, \Delta\chi(\lambda) d\lambda$, $\Delta Y' = \int V'(\lambda)\, \Delta\chi(\lambda) d\lambda$, $\Delta S = \int S(\lambda)\, \Delta\chi(\lambda) d\lambda$

$\Delta L = \int L(\lambda)\, \Delta\chi(\lambda) d\lambda$, $\Delta M = \int M(\lambda)\, \Delta\chi(\lambda) d\lambda$

Hint: the increment SPD (ISPD) is denoted by $\Delta\chi(\lambda)$. This characterizes how the target pops out from the background, in terms of an SPD.

Modelling mesopic spectral sensitivity

If the ISPD is quasi-monochromatic (QM ISPD), with a central wavelength of λ_0 and a total radiance of $\Delta\mu(\lambda_0)$ then, from the *C* formula, with good approximation:

$$V_{mes}(\lambda_0) = 1 / \Delta\mu(\lambda_0) = a_1 V(\lambda_0) + a_2 V'(\lambda_0) + a_3 S(\lambda_0) + a_4 | L(\lambda_0) - 1.25 M(\lambda_0) |$$

A photometric model uses a luminance contrast type quantity: $\Delta Y_{mes,th} = \int V_{mes}(\lambda) \Delta\chi_{th}(\lambda) d\lambda$

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Non-additivity of the photometric model

Photometric model→ using a luminance contrast type quantity:

$$\Delta Y_{mes,th} = \int V_{mes}(\lambda)\, \Delta\chi_{th}(\lambda)\, d\lambda$$

If $\Delta\chi_{th}(\lambda)$ happens to be a QM ISPD then $\Delta Y_{mes,th}$ will be constant, and equal 1 (with good approximation) → $\Delta Y_{mes,th}$ **describes well** the visual targets of **QM ISPDs**.

But if $\Delta\chi_{th}(\lambda)$ is not a QM ISPD (i.e. a composite SPD) then

$$\Delta Y_{mes,th} = 1 + \left(a_4 \int | L(\lambda) - 1.25\, M(\lambda) |\ \Delta\chi_{th}(\lambda) d\lambda \right) - a_4 \left| \int L(\lambda)\, \Delta\chi_{th}(\lambda) d\lambda - 1.25 \int M(\lambda)\, \Delta\chi_{th}(\lambda) d\lambda \right| = 1 + NA$$

For any QM ISPD, NA=0 (with good approx.)

The reason of NA≠0 is the |L-M| term.

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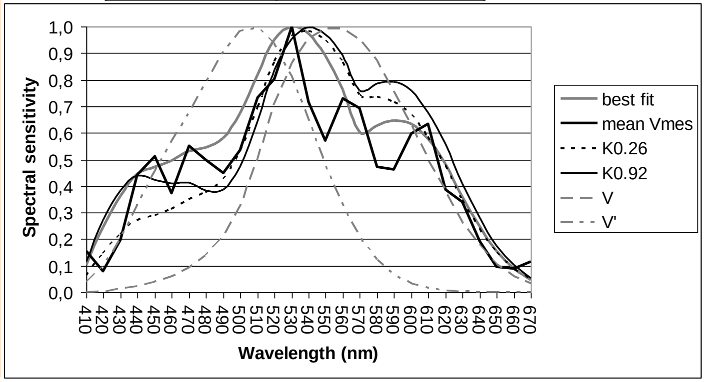
Application to an experimental dataset

- Parameters a_1, a_2, a_3, and a_4 estimated from a mesopic detection threshold dataset
  - consisting of **QM** ISPDs resulting from a psycho-physical experiment
    - the detection threshold criterion for 2° filled disk targets presented for 2s at 20° off-axis on a fixed, uniform mesopic background illuminated by white phosphor LEDs at 0.5cd/m^2

a_1	0.484
a_2	0.248
a_3	0.273
a_4	0.582



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Sample NA computation-1

- Predicted values of NA
- white LED light source
- 5 MacBeth Color Checker Chart reflecting samples
- predicting the absolute ISPD for C=1 i.e. for the detection threshold

Sample	NA
#6 (bluish green)	0.122
#15 (red)	0.140
#16 (yellow)	0.318
#17 (magenta)	0.214
#19 (white)	0.221

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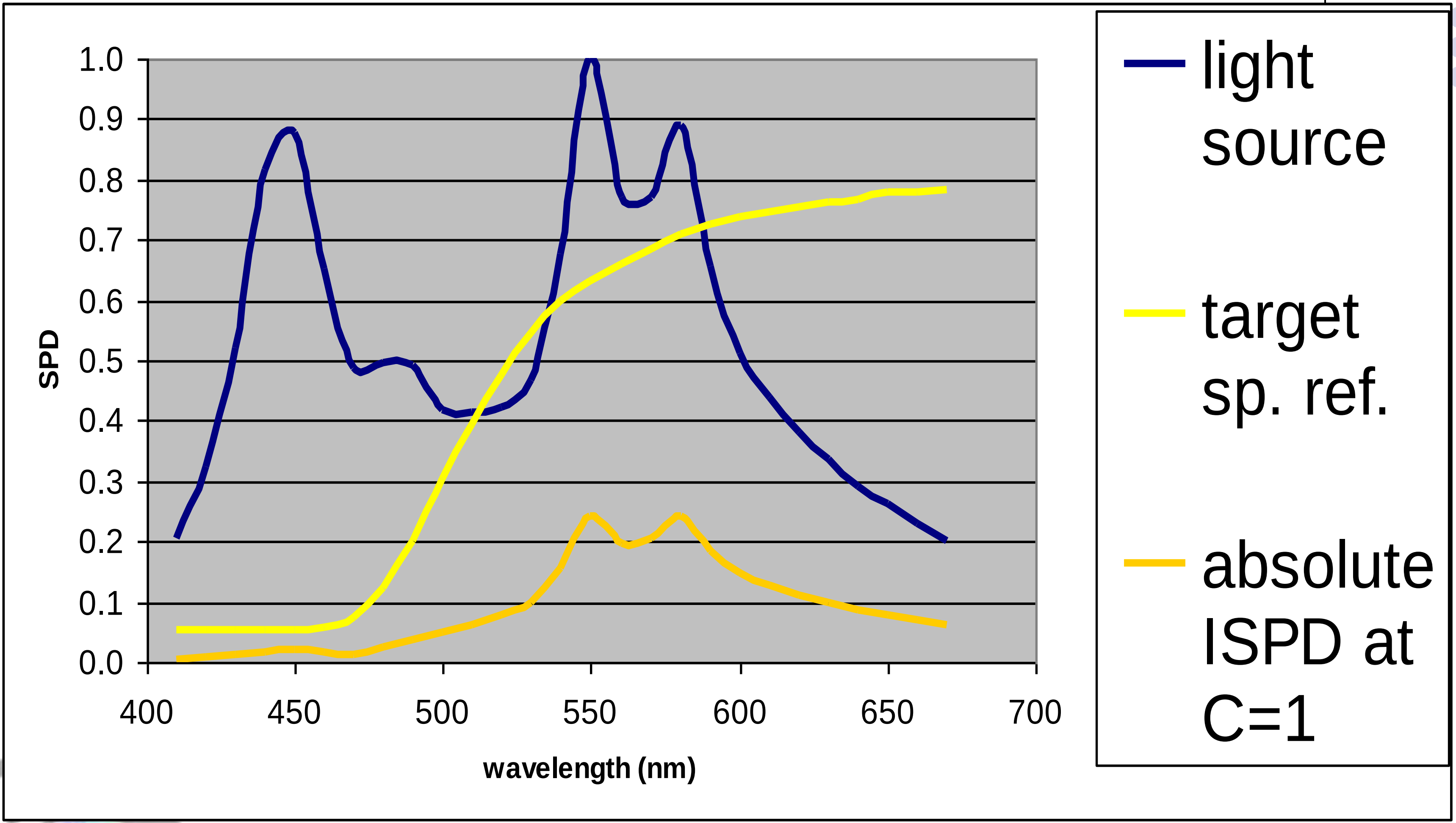
Sample NA computation-2



The above graph shows the „absolute” ISPD necessary to achieve the detection threshold (*C*=1) for a yellow target (similar to a life vest)

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Comparison of different *C*-formulae-1

$$C_1 = a_1\Delta Y + a_2\Delta Y' + a_3\Delta S + a_4 | \Delta L - 1.25\,\Delta M |$$

$$C_2 = a_1\Delta Y + a_2\Delta Y' + a_3\Delta S + a_4 | \Delta L - 1.25\,\Delta M | + a_5 | \Delta L + 1.5\Delta M - 0.6\Delta S |$$

$$C_3 = a_1\Delta Y + a_2\Delta Y' + a_3\Delta S + a_4 | \Delta L - 1.25\,\Delta M | + a_5 | \Delta L + 1.5\Delta M - 0.6\Delta S | + a_6 | \Delta L - 1.5\Delta M - 0.6\Delta S |$$

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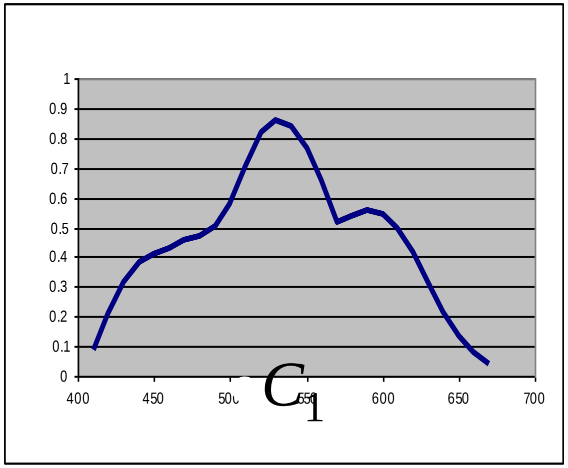
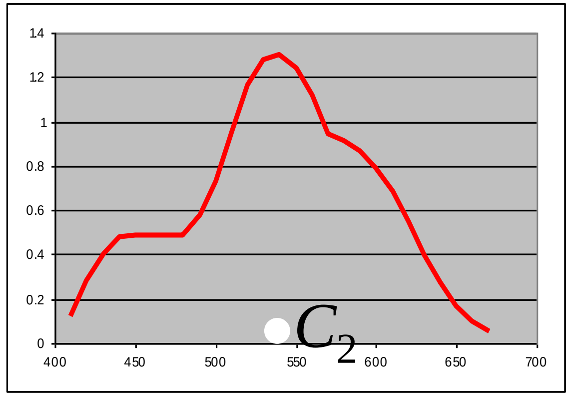
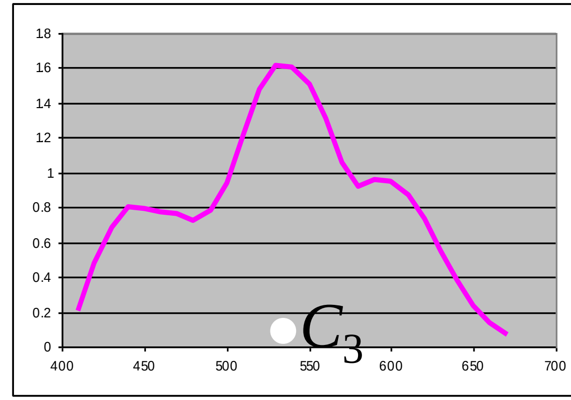
Comparison of different C-formulae-2







Yellow NA:	0.318	0.195	0.301
Magenta NA:	0.214	0.275	0.417
Red NA:	0.140	0.131	0.393
White NA:	0.221	0.218	0.252
Bluish gr. NA:	0.122	0.139	0.149

Conclusions

- A mesopic contrast type quantity (*C*) with chromatic (opponent) terms may better describe a typical road lighting situation (where target detection is important) than a mesopic luminance based quantity
- From the *C*=const. criterion (C=1 at threshold), we can compute the necessary amount of irradiance if the relative SPD of the light source is given
- Using a luminance contrast type descriptor causes chromaticity dependent non-additivity (NA) error
- The value of NA was computed for a set of reflecting samples

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Outlook-1

- Other important objects shall be investigated in the future
  - traffic signs, life vests, other clothing, retro-reflective materials, wild animals
- The *C*=const. criterion may help compute the radiance necessary for object detection
  - and thus select the best light source for a set of important objects
    - including achromatic or near-achromatic objects
    - to be detected in a specific application e.g. night-time driving

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Outlook-2

- Enhancement of the *C*-formula by adding other possible retinal mechanisms
  - |L+M-S| or |S-(L-M)| or |S-(M-L)|
  - **deciding will be the result of psycho-physical experiments**
    - currently underway at the Laboratory of Lighting Technology of the TU Darmstadt and the Virtual Environment and Imaging Technologies Laboratory of the Faculty of Information Technology at the University of Pannonia

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Outlook-3

- From the *C*=const. criterion we can estimate the parameter set a={a_i} and set up the multi-peak spectral sensitivity curve *from only a few* psycho-physically measured detection contrast thresholds
  - from 6 absolute iSPDs measured at the detection threshold (red, green, blue, yellow, cyan, and magenta i.e. fixed relative ISPDs) it may be possible to estimate the parameter set a.
  - we may not have to cover the whole visible spectrum with QM ISPD stimuli during the psycho-physical measurement
- We can use different parameter sets a for each mesopic adaptation level (A) and each stimulus eccentricity (ε)
  - The relationship a=a(A,ε) may be used to characterize the mesopic adaptation level i.e. to describe the effect of changing the fixed mesopic background or the eccentricity of appearance on the detection threshold