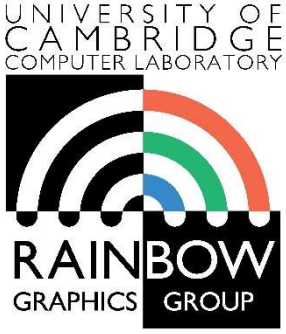
Colour contrast sensitivity and image appearance

Rafał Mantiuk



Acknowledgements

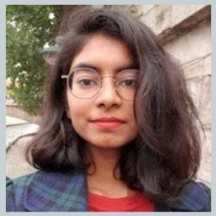
European Research Council

EPSRC
Engineering and Physical Sciences Research Council

UNIVERSITY OF CAMBRIDGE

PRIFYSGOL BANGOR UNIVERSITY

UNIVERSITY OF LIVERPOOL



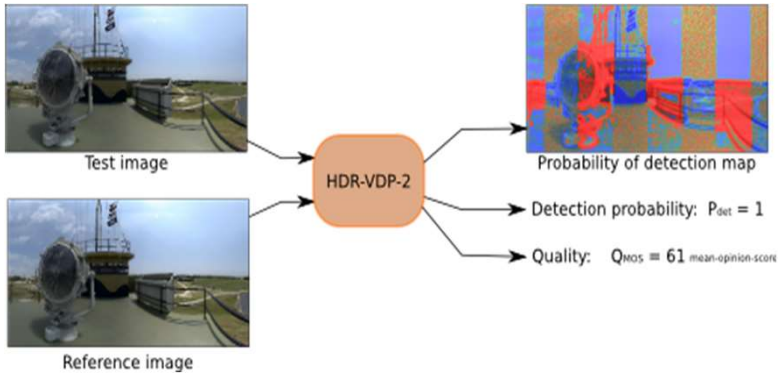
1495 UNIVERSITY OF ABERDEEN

What do we do?

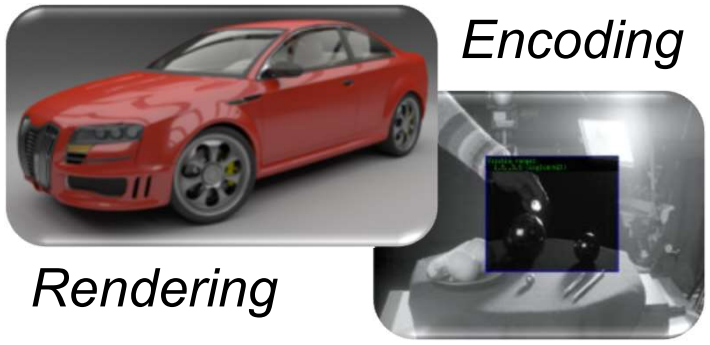
Build prototype displays

Collect visual data with psychophysics/psychometrics

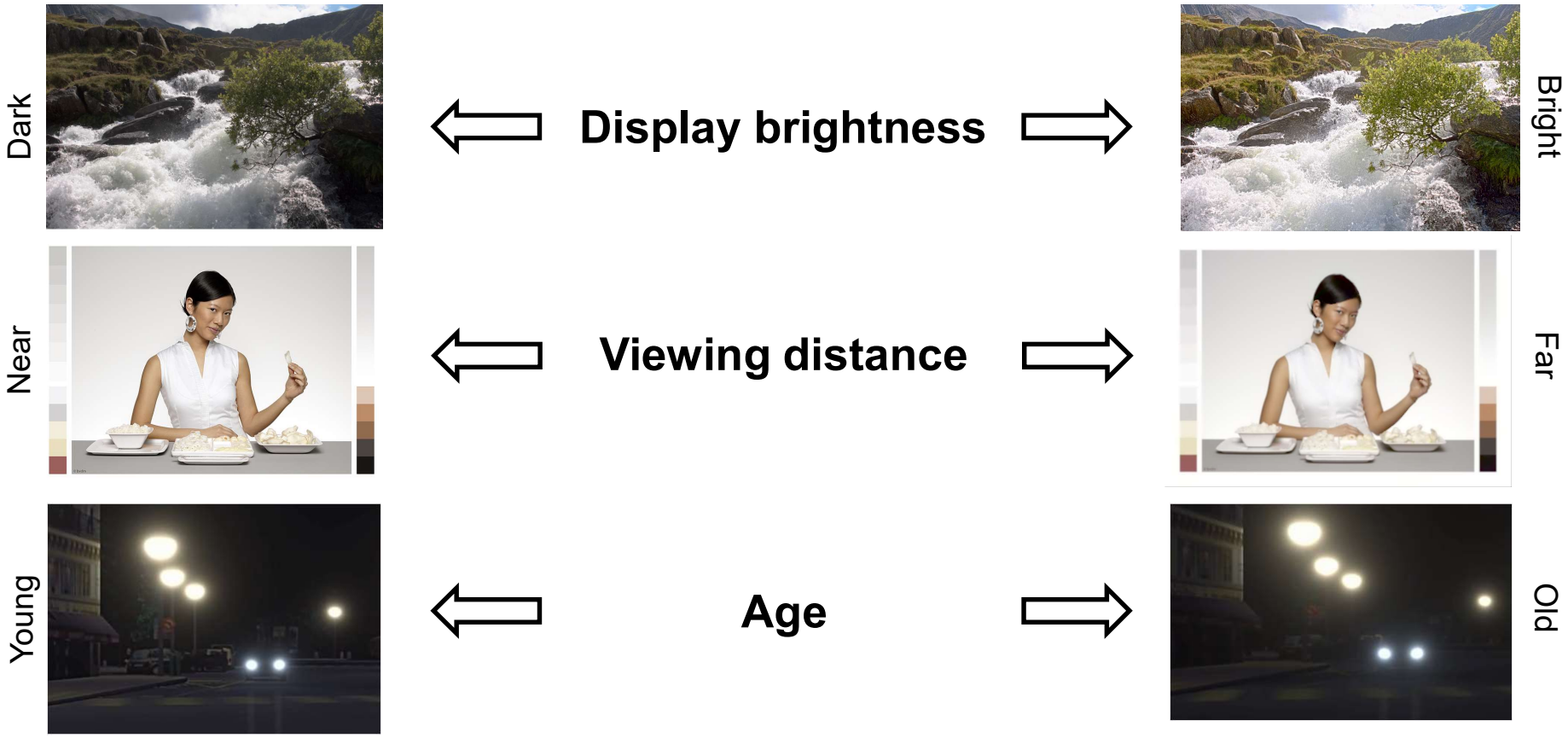
Create visual models



Use in perception-optimized applications



Goal: To match colour and contrast appearance across viewing conditions



Dark-display compensation

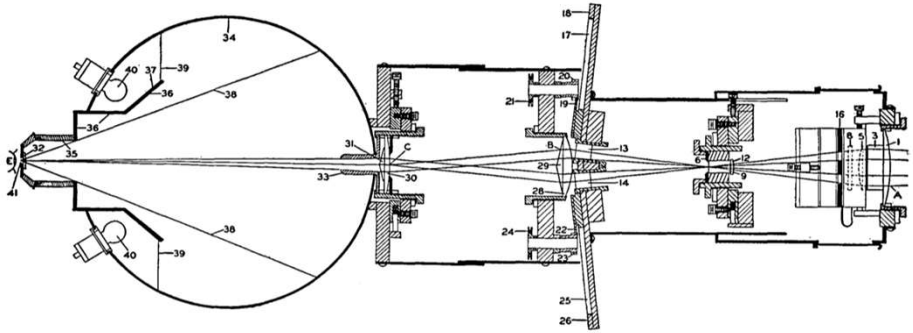
- Match the appearance of bright image on a dark display
  - or the opposite
- Method:
  - Model night vision, compensate for it
- Improves image quality on a dimmed display
  - Lower power consumption, less eye fatigue

CIC28
ONLINE
Twenty-eighth Color and Imaging Conference
4-19 November 2020

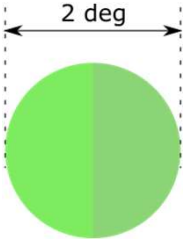
OmniCSF

Spatio-chromatic contrast sensitivity

Colour discrimination

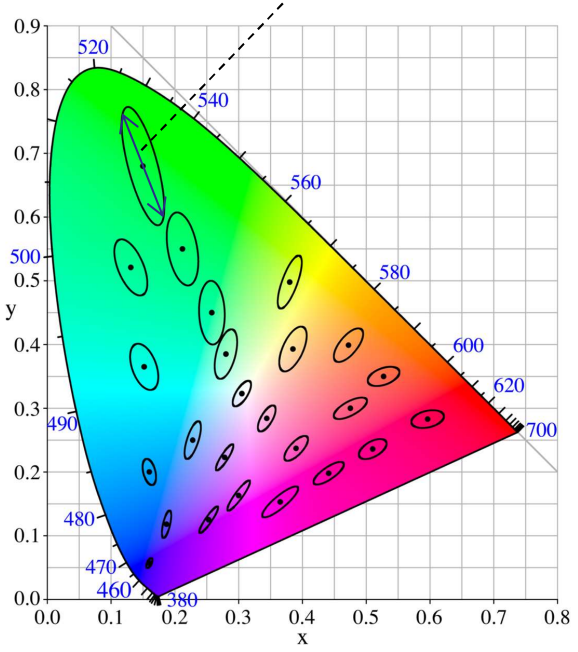


[MacAdam (1942). Visual Sensitivities to Color Differences in Daylight. *JOSA]*



50 x colour matching

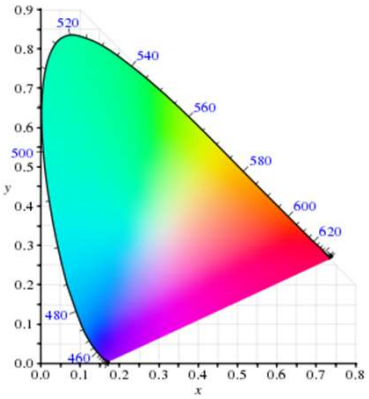
std of colour matches



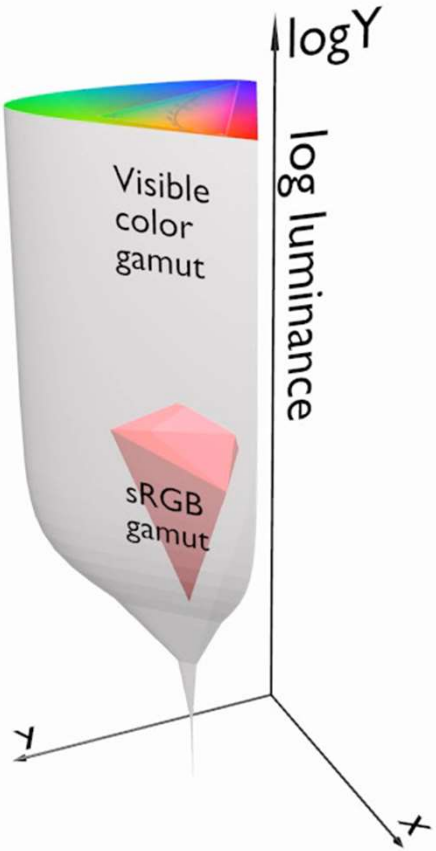
- Colour discrimination for 2 deg half-discs
- How can we model colour discrimination that can generalize to complex images?

The fallacy of flat colour gamut

2D projection of a visible colour gamut

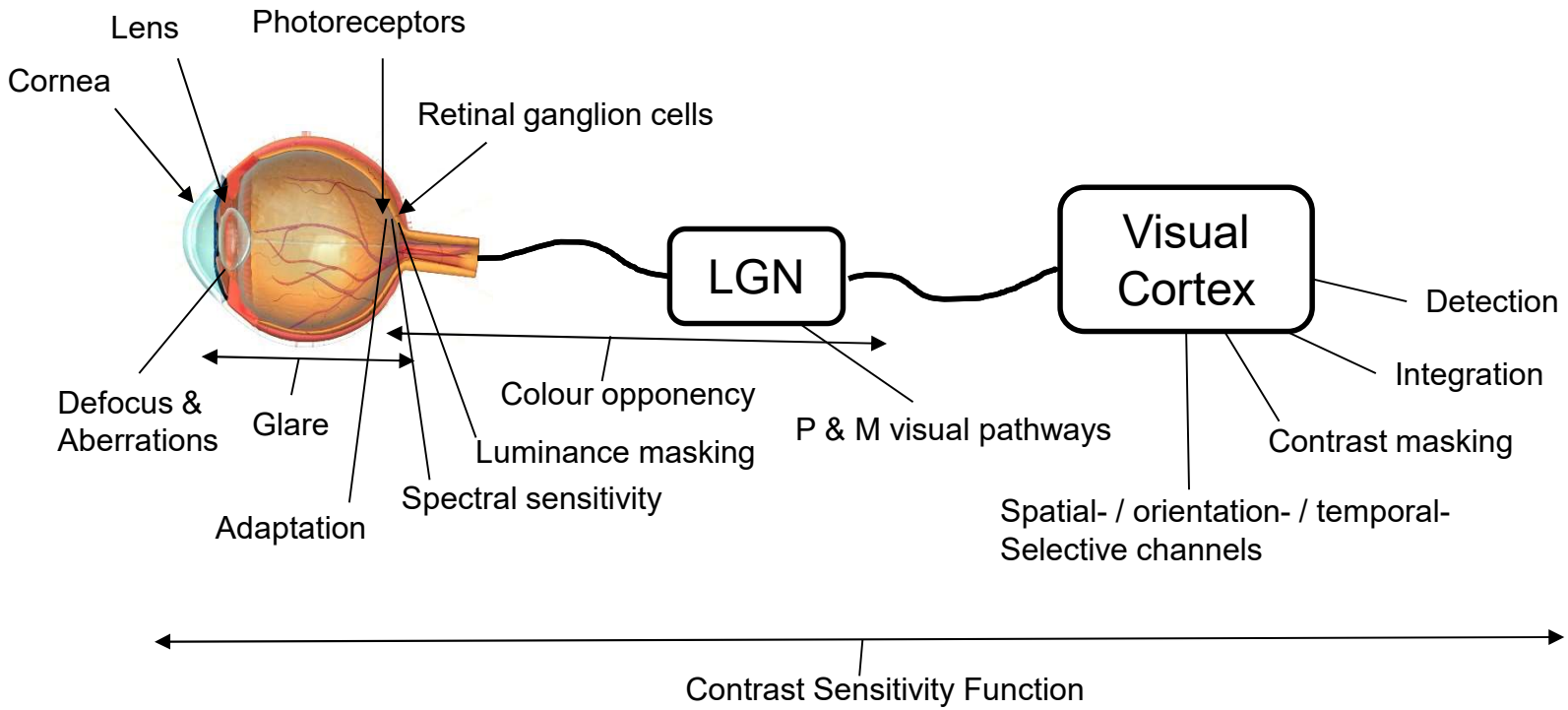


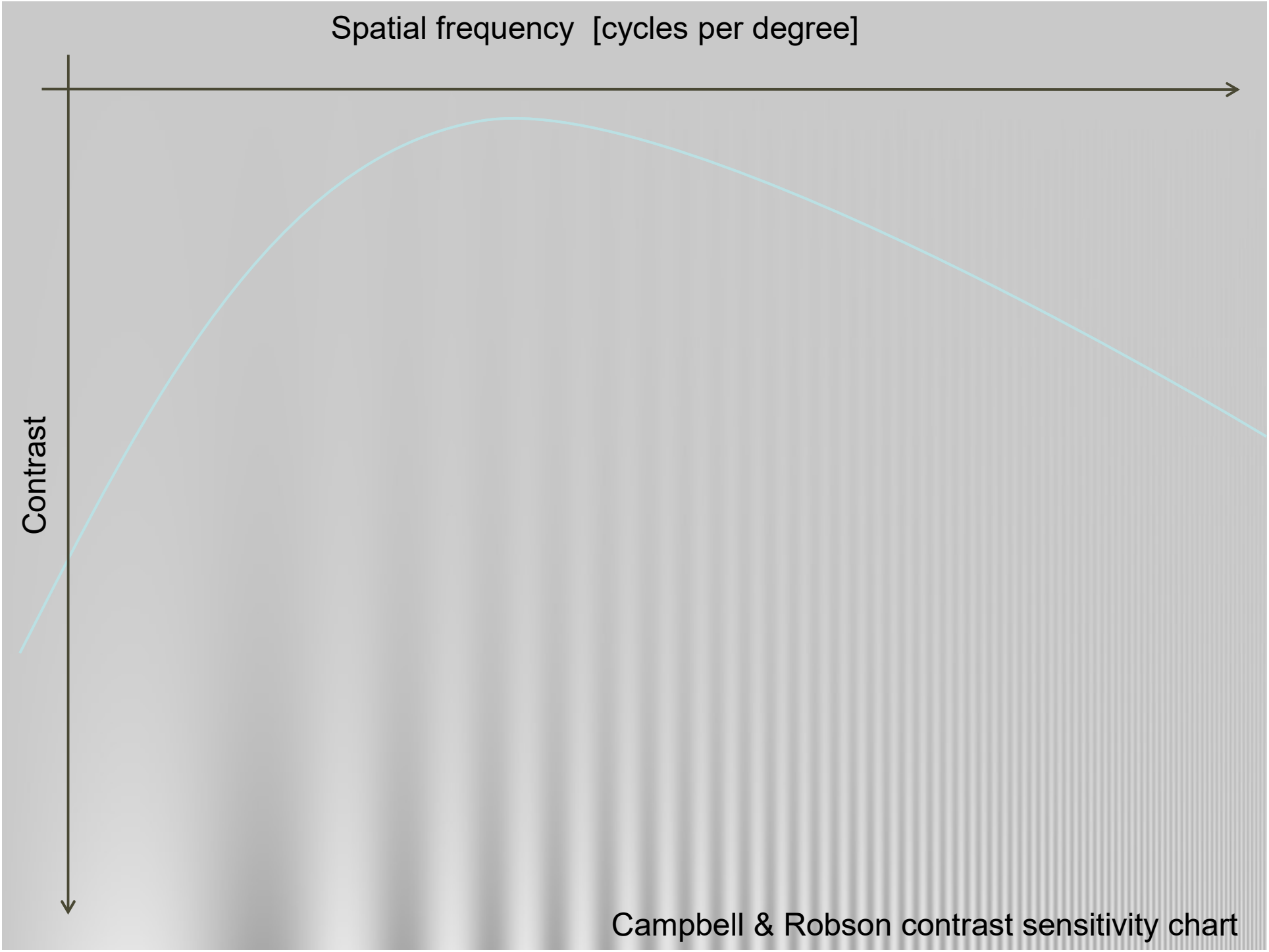
- Colour gamut is a 3D solid
  - We need to consider all dimensions
  - Luminance is often more important than chromaticity
- Visible colour gamut is larger than what is encoded in popular colour spaces
  - sRGB, Lab, Luv, …



Visible vs. sRGB colour gamut

Modeling visual system



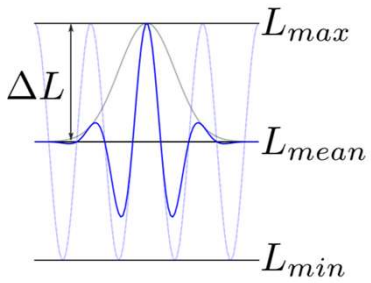

Spatial frequency [cycles per degree]
Contrast
Campbell & Robson contrast sensitivity chart

Spatio-chromatic CSF

Contrast and Sensitivity

- Contrast

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} = \frac{\Delta L}{L_{mean}}$$



- Contrast detection threshold (or detection threshold)
  - A small contrast C_t that is detectable by an average observer with 75% probability
- Sensitivity
  - The inverse of the detection threshold

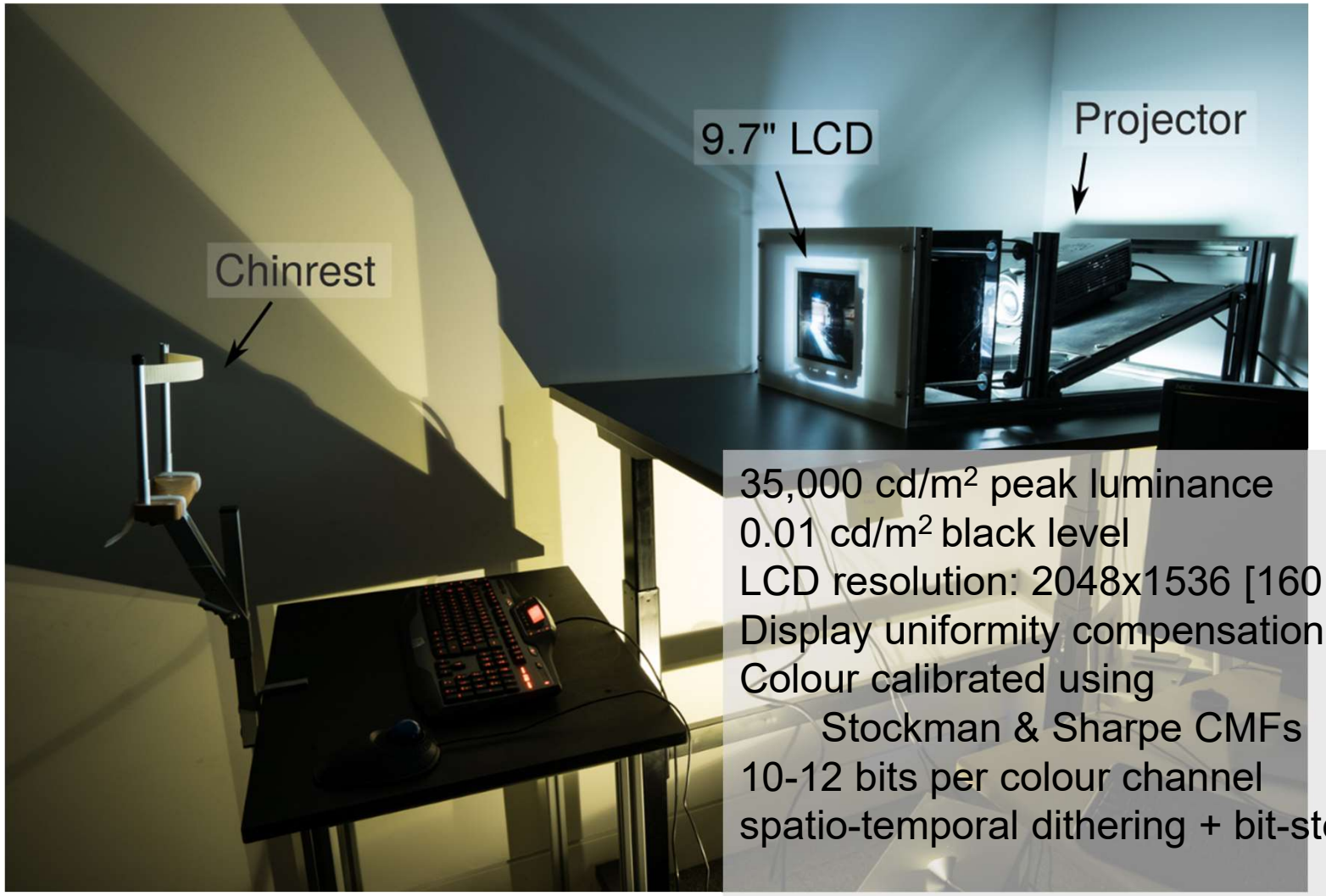
$$S = \frac{1}{C_t}$$

Datasets

- 5 datasets measuring spatio-chromatic CSF
  - natural viewing

Dataset	Color modulation directions	Frequencies	Size	Background luminance	Background chromaticities
Wuerger et al. 2002 [11]	7: Black-White, Green-Red, YellowGreen-Violet, Greenish-Pink, Yellow-Blue, DarkGreen-LightPink, DarkYellow-LightBlue	1–32 cpd	0.5 deg, fixed size	40 cd/m^2	custom gray
Mantiuk et al. 2011 [2]	1: Black-White	0.125–32 cpd	0.15, 0.5, 1.5 deg, fixed size	0.0002–150 cd/m^2	D65
Kim et al. 2013 [12]	4: Green-Red, YellowGreen-Violet, DarkGreen-LightPink, DarkYellow-LightBlue	0.25–16 cpd	1.5, 3 deg, fixed size^2	0.02–200 cd/m^2	D65
Xu et al. 2020 [13, 14]	9 directions on the isoluminant plane	0.06–3.84 cpd	9.3 deg, fixed size	8.2–70 cd/m^2	gray, red, green, yellow and blue
Wuerger et al. 2020 [8]	3: Black-White, Green-Red, YellowGreen-Violet	0.125–6 cpd	0.0417–4 deg, fixed cycles	0.02–10 000 cd/m^2	D65

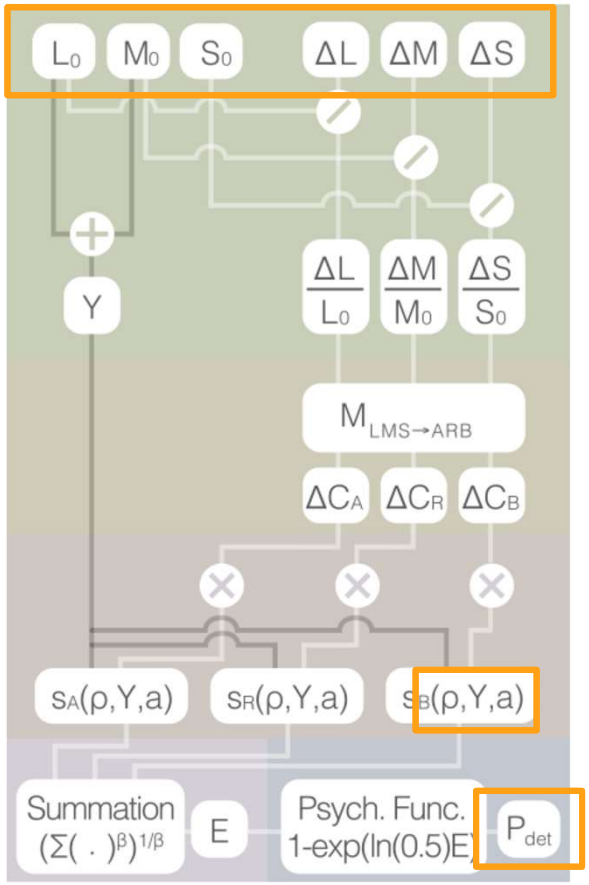
CSF measurements on HDR display



35,000 cd/m^2 peak luminance
0.01 cd/m^2 black level
LCD resolution: 2048x1536 [160 ppd]
Display uniformity compensation
Colour calibrated using
Stockman & Sharpe CMFs
10-12 bits per colour channel
spatio-temporal dithering + bit-stealing

[Wuerger et al. 2020, JoV]

CSF Model: Cone-contrast



Input:

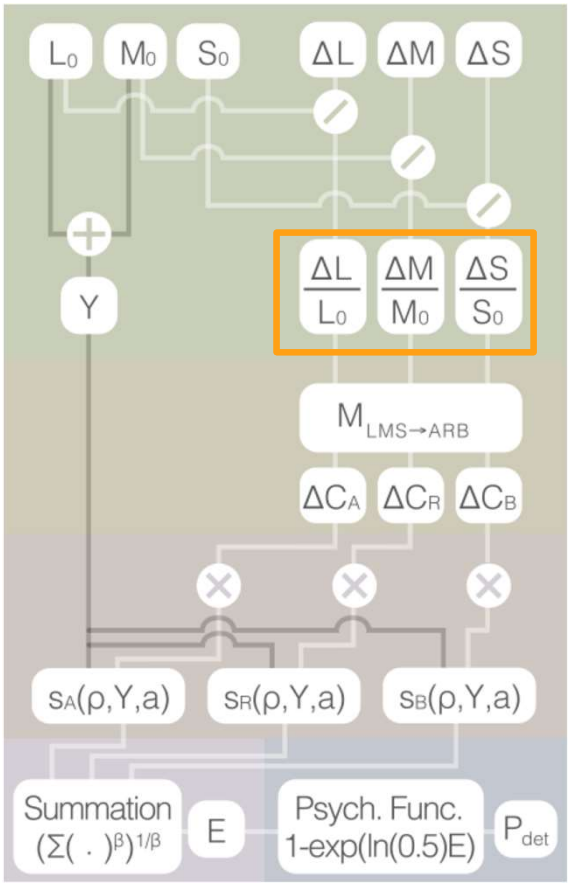
Background colour	$L_0M_0S_0$
Colour direction	ΔLMS
Spatial frequency	ρ [cycles per degree]
Luminance	Y [cd/m^2]
Stimulus size	a [deg^2]

Output:

Probability of detection	P_{det}

Probability of detecting a Gabor on background $L_0M_0S_0$ and amplitude ΔLMS

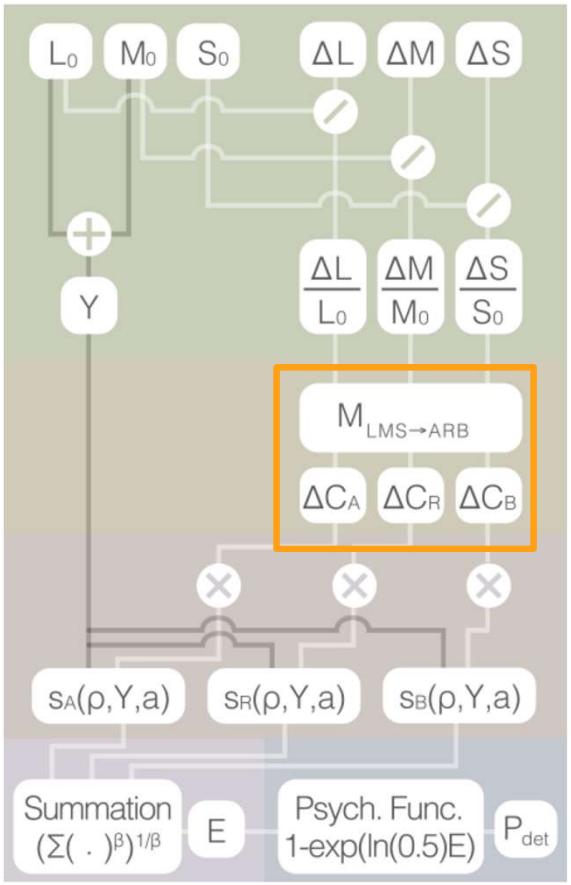
CSF Model: Cone-contrast



Cone contrast accounts for colour adaptation

$$\begin{bmatrix} \frac{\Delta \mathfrak{L}}{\mathfrak{L}_0} \\ \frac{\Delta \mathfrak{M}}{\mathfrak{M}_0} \\ \frac{\Delta \mathfrak{S}}{\mathfrak{S}_0} \end{bmatrix}$$

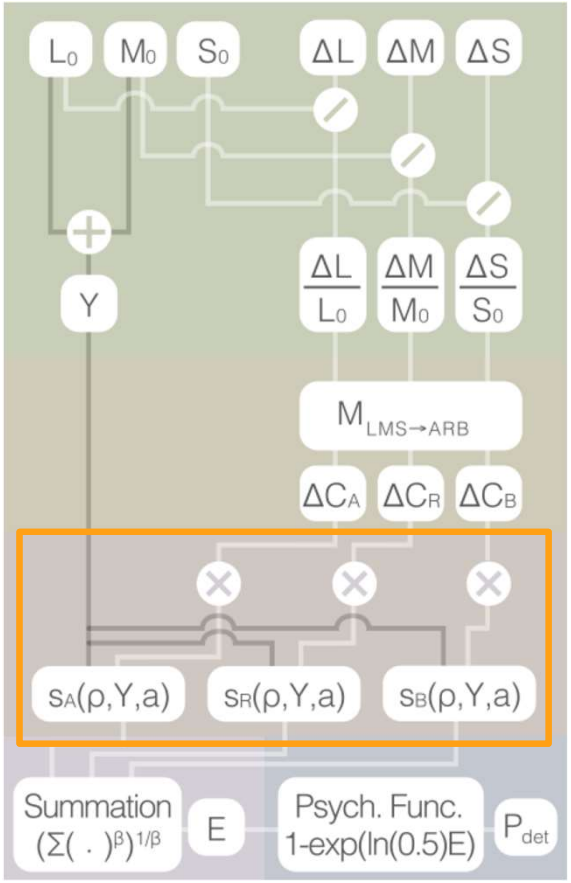
CSF Model: Cone-contrast



Colour opponent responses

$$\begin{bmatrix} \Delta C_A \\ \Delta C_R \\ \Delta C_B \end{bmatrix} = \begin{bmatrix} 1 & m_{1,2} & m_{1,3} \\ 1 & -m_{2,2} & m_{2,3} \\ -m_{3,1} & -m_{3,2} & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{\Delta \mathfrak{L}}{\mathfrak{L}_0} \\ \frac{\Delta \mathfrak{M}}{\mathfrak{M}_0} \\ \frac{\Delta \mathfrak{S}}{\mathfrak{S}_0} \end{bmatrix}$$

CSF Model: Cone-contrast



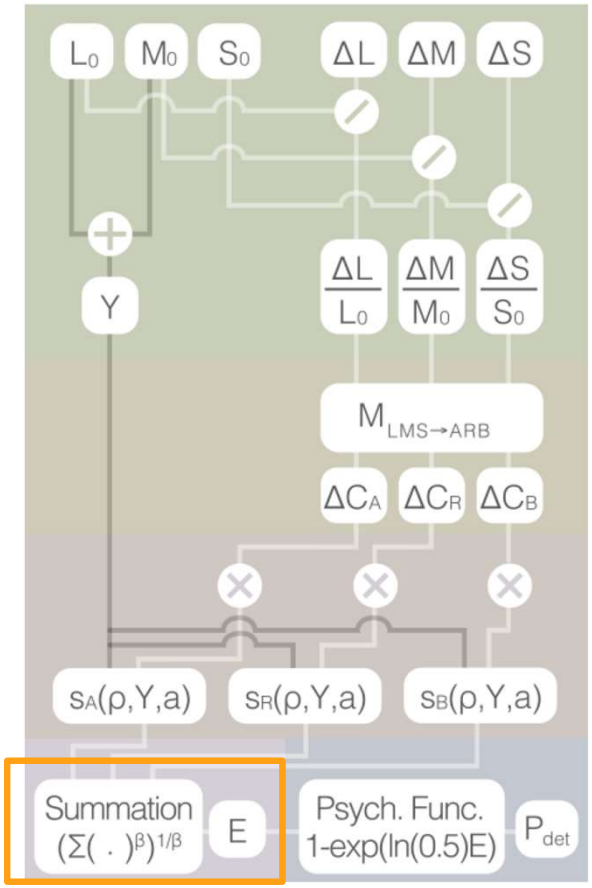
Per-mechanism non-linearities

Frequency: Log-parabolas

Size: Rovamo's model [1993]

Luminance: hyperbolic functions

CSF Model: Cone-contrast



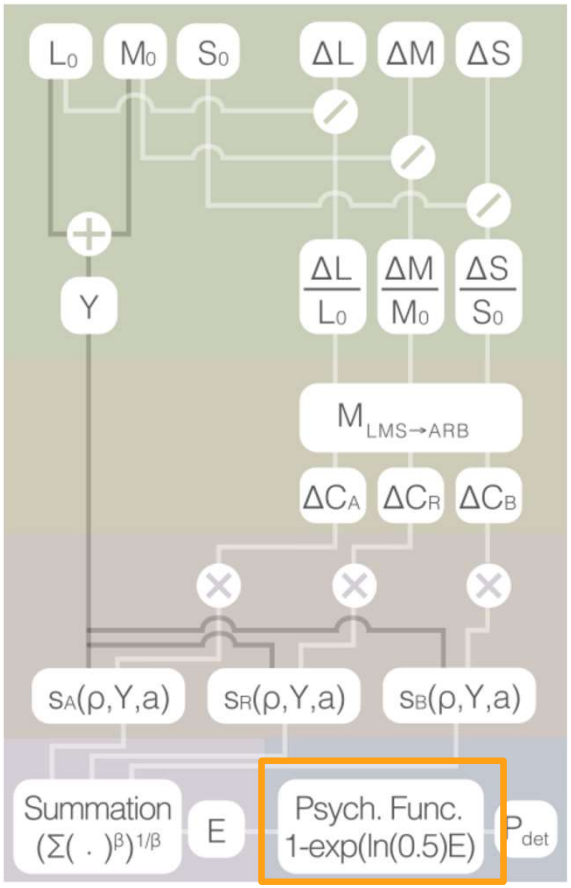
Probability summation

$$E = \left(\sum_{c \in \{A,R,B\}} (s_c(\rho, Y, a)\, \Delta C_c)^{\beta} \right)^{1/\beta}$$

Slope of the psychometric function

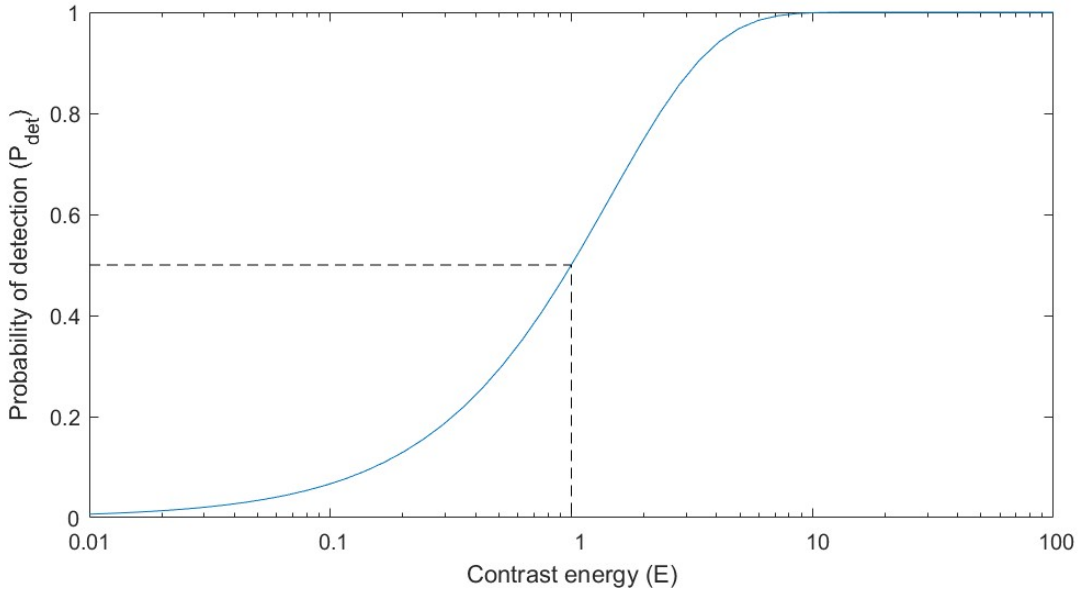
Across three colour mechanisms

CSF Model: Cone-contrast

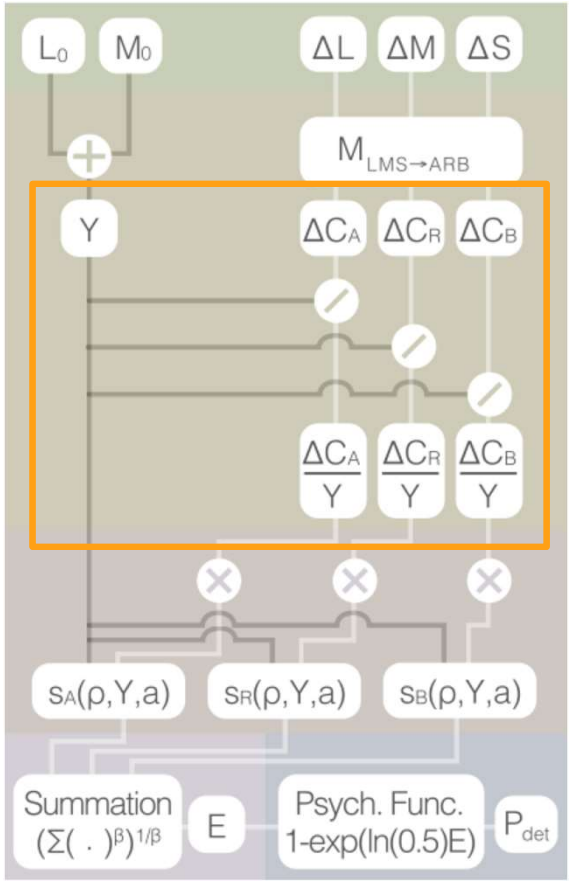


Psychometric function

$$P_{det} = 1 - \exp\left(\ln(0.5)E\right)$$



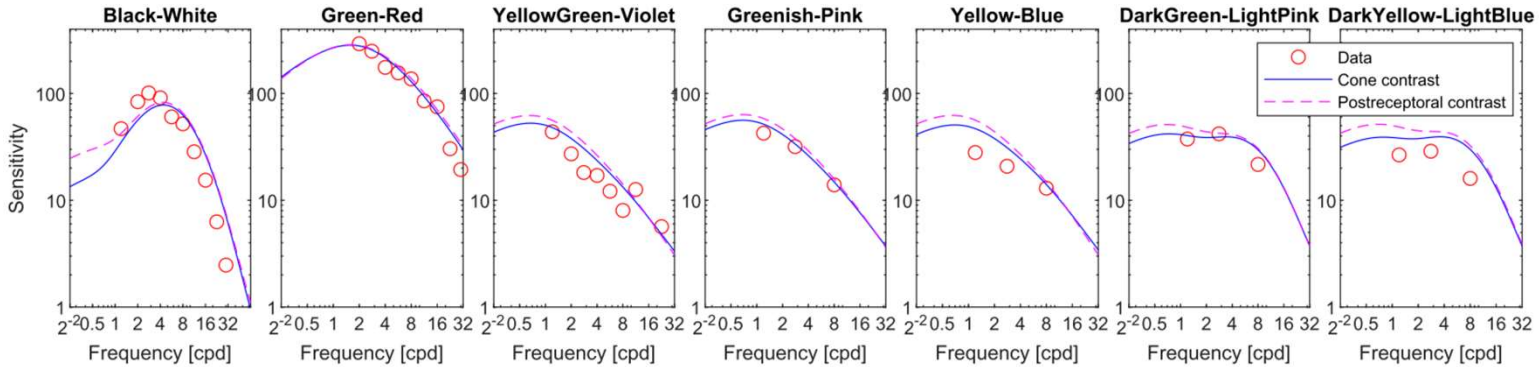
CSF Model: Postreceptoral contrast



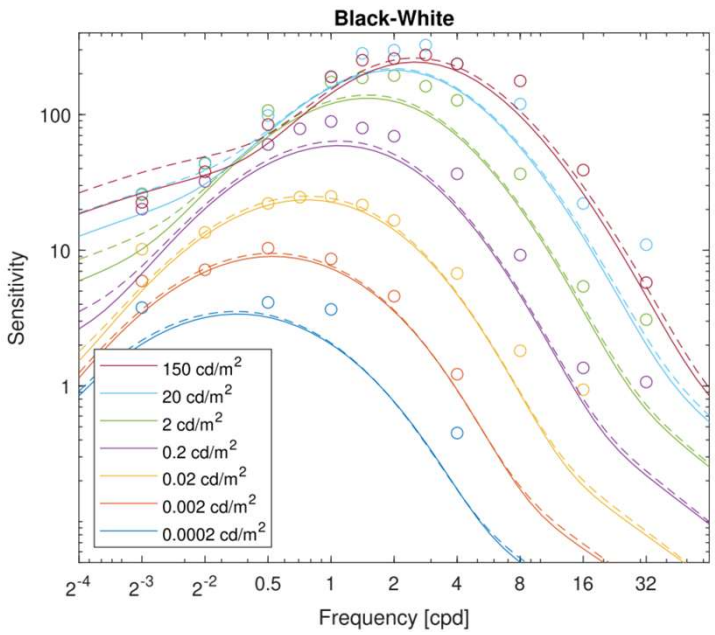
Contrast computed on the responses of the mechamisms

$$\Delta C_A = \frac{\Delta C'_A}{Y}, \quad \Delta C_R = \frac{\Delta C'_R}{Y}, \quad \Delta C_B = \frac{\Delta C'_B}{Y}$$

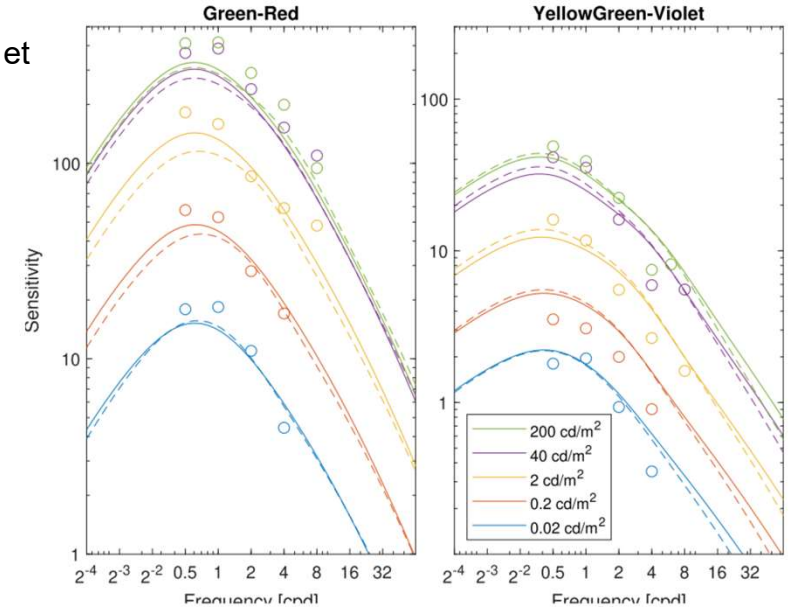
Fitting the data



[Wuerger et al. 2002]

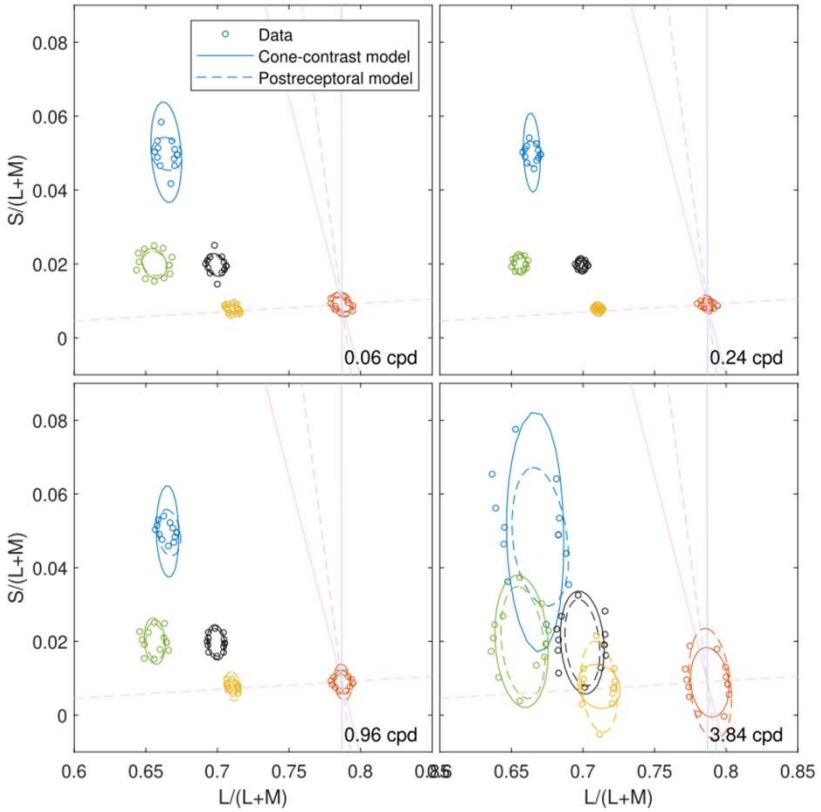


[Mantiuk et al. 2011]

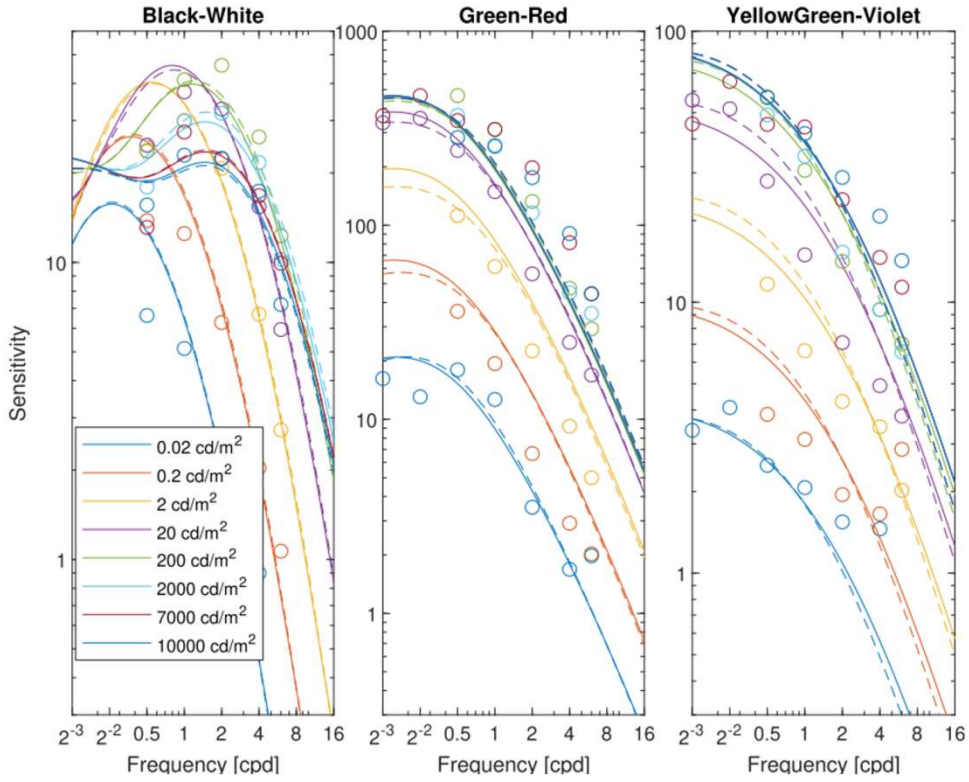


[Kim et al. 2013]

Fitting the data



[Xu et al. 2020]

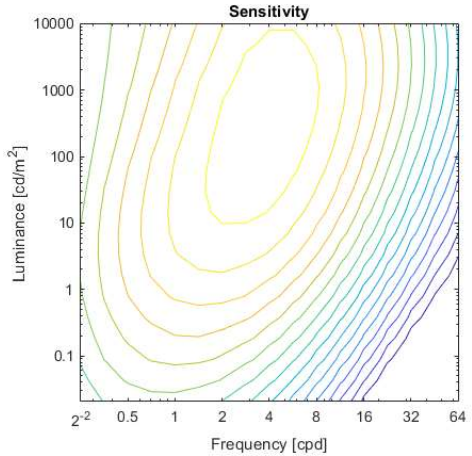


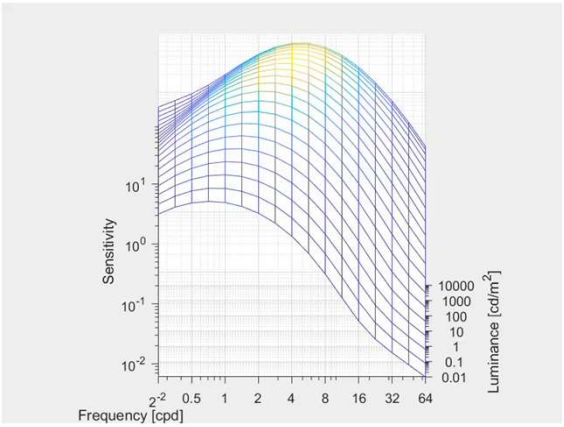
[Wuerger et al. 2020]

Model predictions

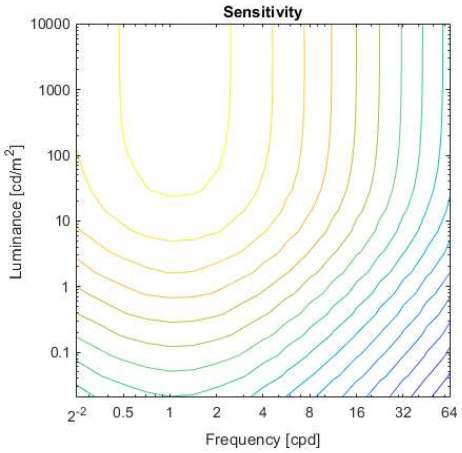
- CSF as a function of background colour, **luminance**, colour direction, **frequency** and size

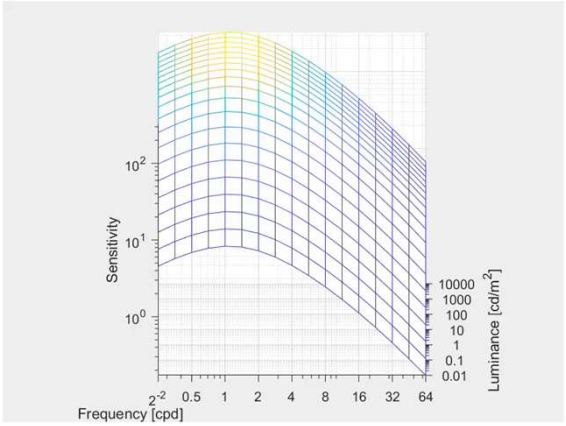
Black-White



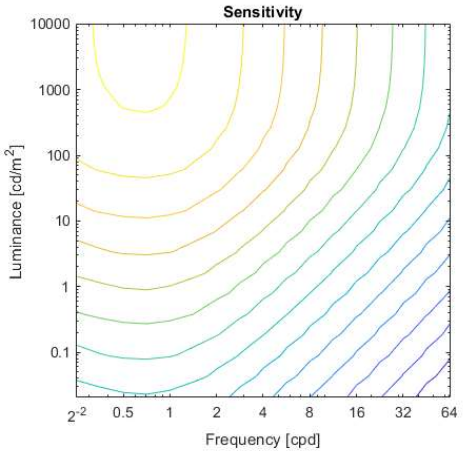


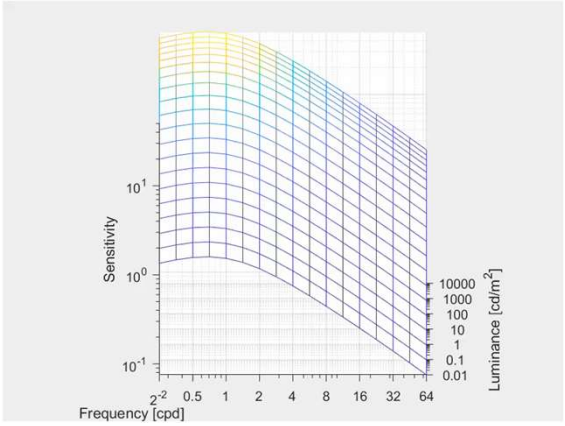
Red-Green





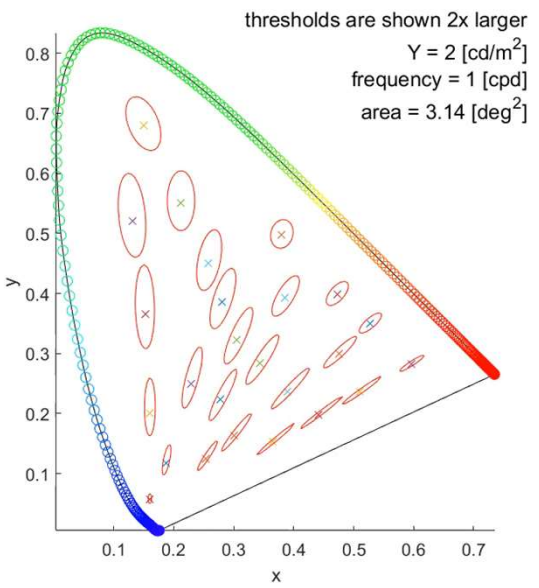
Violet-Yellow

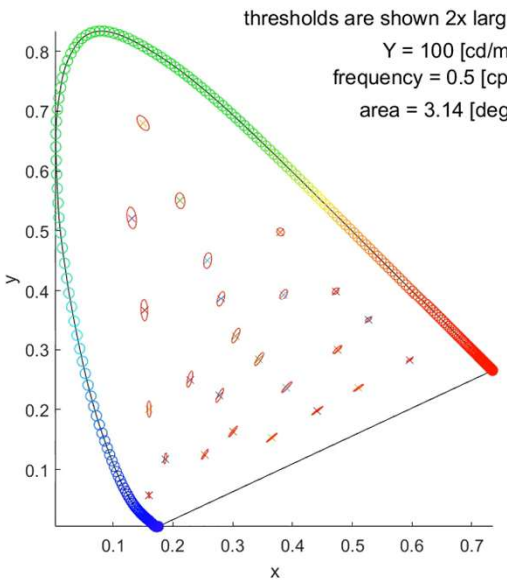


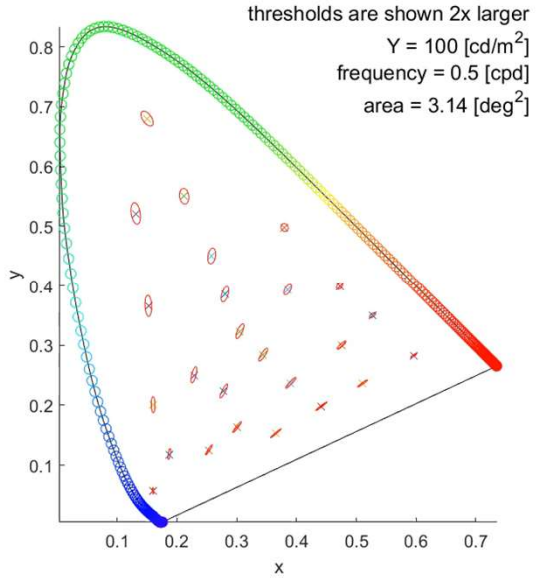


New CSF for colour discrimination

- Colour discrimination as a function of
  - Background colour and luminance [LMS]
  - Spatial frequency [cpd]
  - Size [deg]





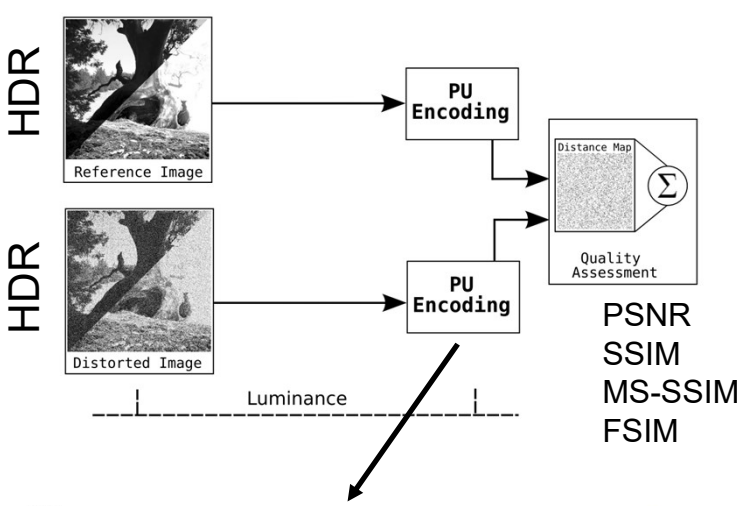


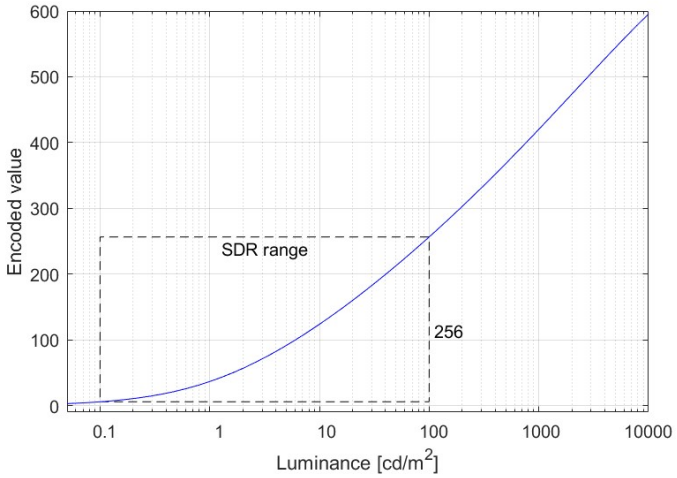
OmniCSF

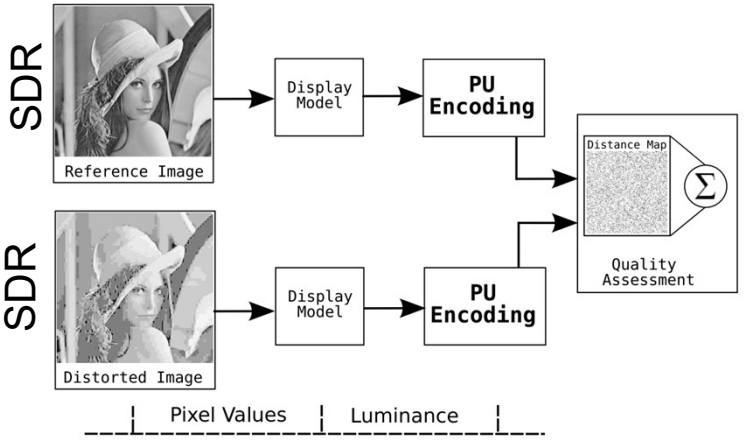
- New *practical* colour CSF that models
  - All spatial dimensions of stimuli
  - For all visible colours (HDR)
  - For natural viewing (and complete adaptation)
- Applications
  - Visual difference models (for complex images)
    - HDR-VDP
  - Better coding of HDR colour
    - Improved PQ, perceptually uniform coding
  - …
- More details, data and code:
  https://www.cl.cam.ac.uk/research/rainbow/projects/hdr-csf/

Applications of OmniCSF

Adapting image quality metrics for HDR







- To run SDR quality metrics on HDR images
- To make SDR quality metrics sensitive to display brightness

Age-adaptive coding

- Pre-filter an image before image compression
- Original PNG: 6.4 bpp

Filtered for 24-year old
4.05 bpp

Filtered for 65-year old
3.78 bpp

Filtered for 80-year old
3.709 bpp

Viewing-distance adaptive coding

- Pre-filter an image before image compression
- Original PNG: 6.4 bpp

Filtered for 0.5 m
4.05 bpp

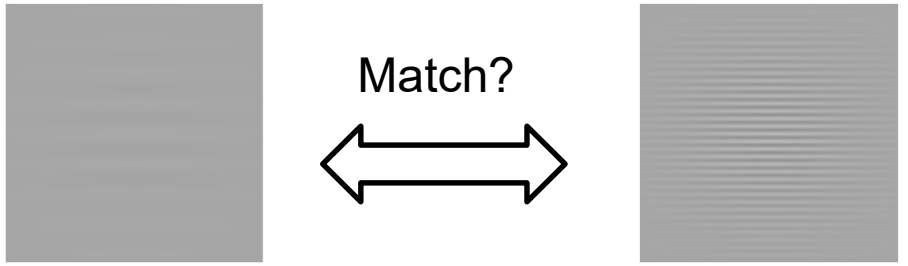
Filtered for 1 m
3.56 bpp

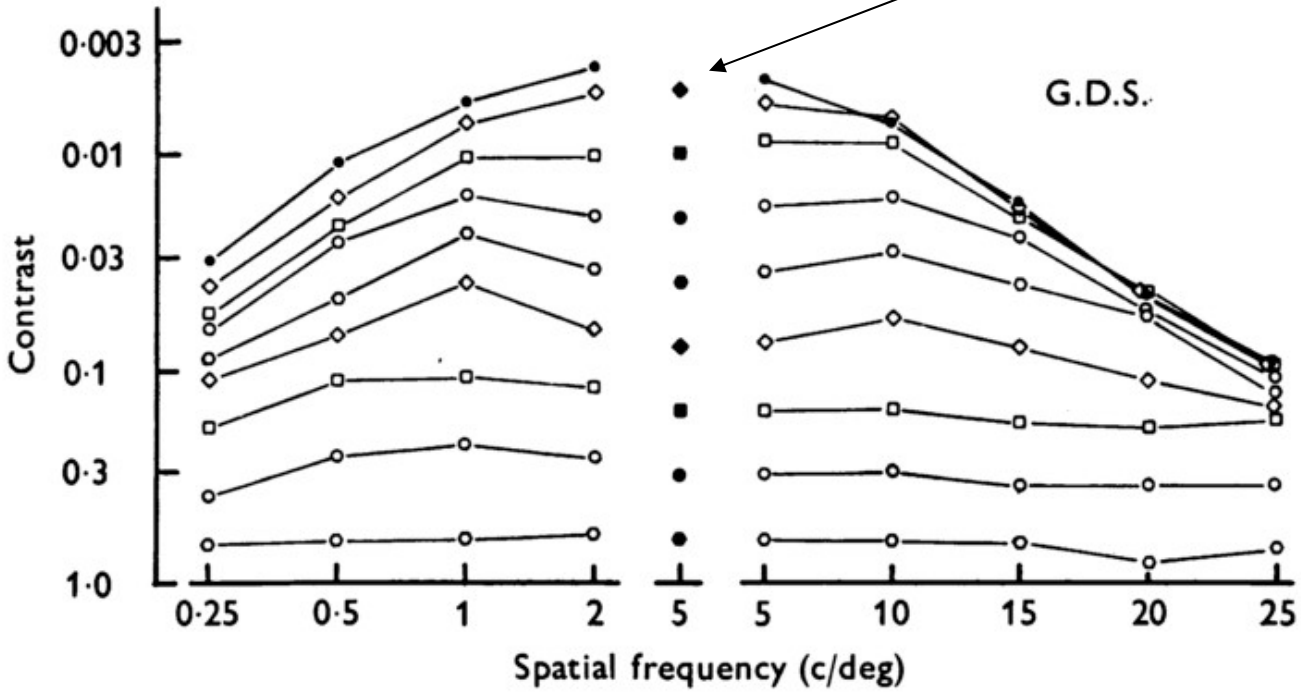
Filtered for 2 m
3.39 bpp

Contrast matching

Contrast constancy

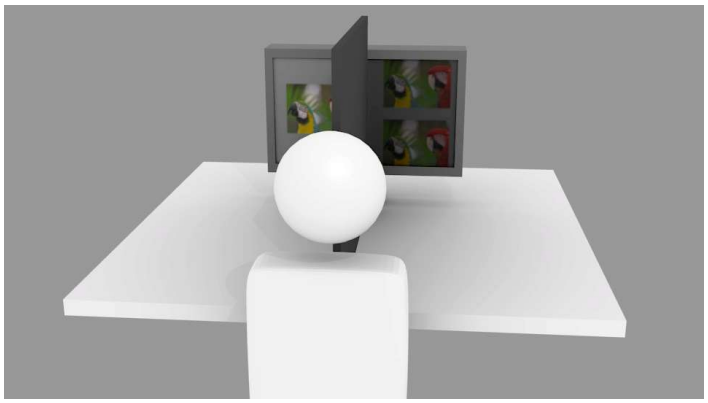
Experiment: Adjust the amplitude of one sinusoidal grating until it matches the perceived magnitude of another sinusoidal grating.





From: Georgeson and Sullivan. 1975. J. Phsysio.

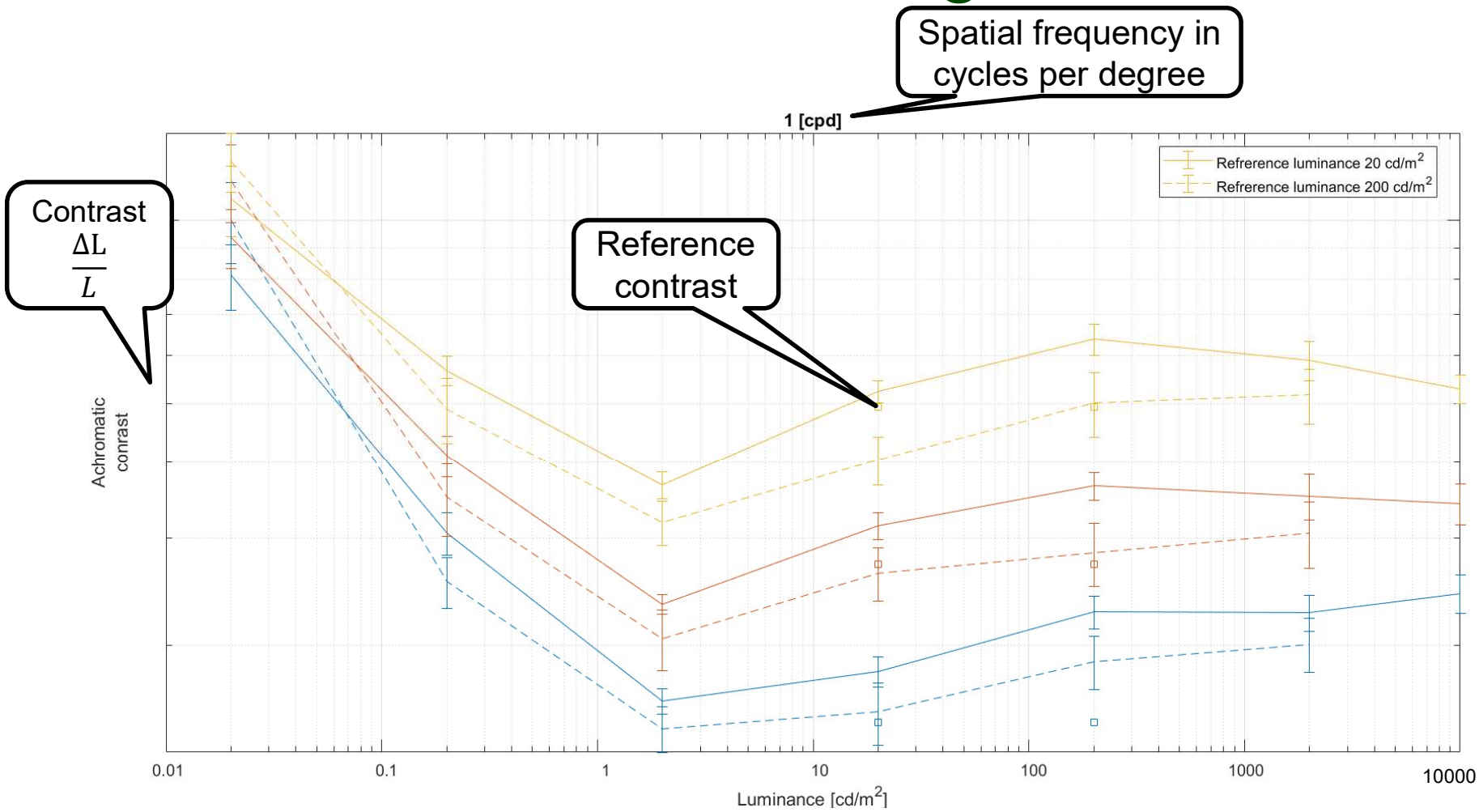
Experimental set-up



- Appearance matching
  - Each eye adapted to different luminance level
  - No binocular fusion
- The task
  - Method of adjustment
  - Adjust the contrast of the test stimulus to match the contrast of the reference stimulus
  - Matching of Gabor patches of the same frequency

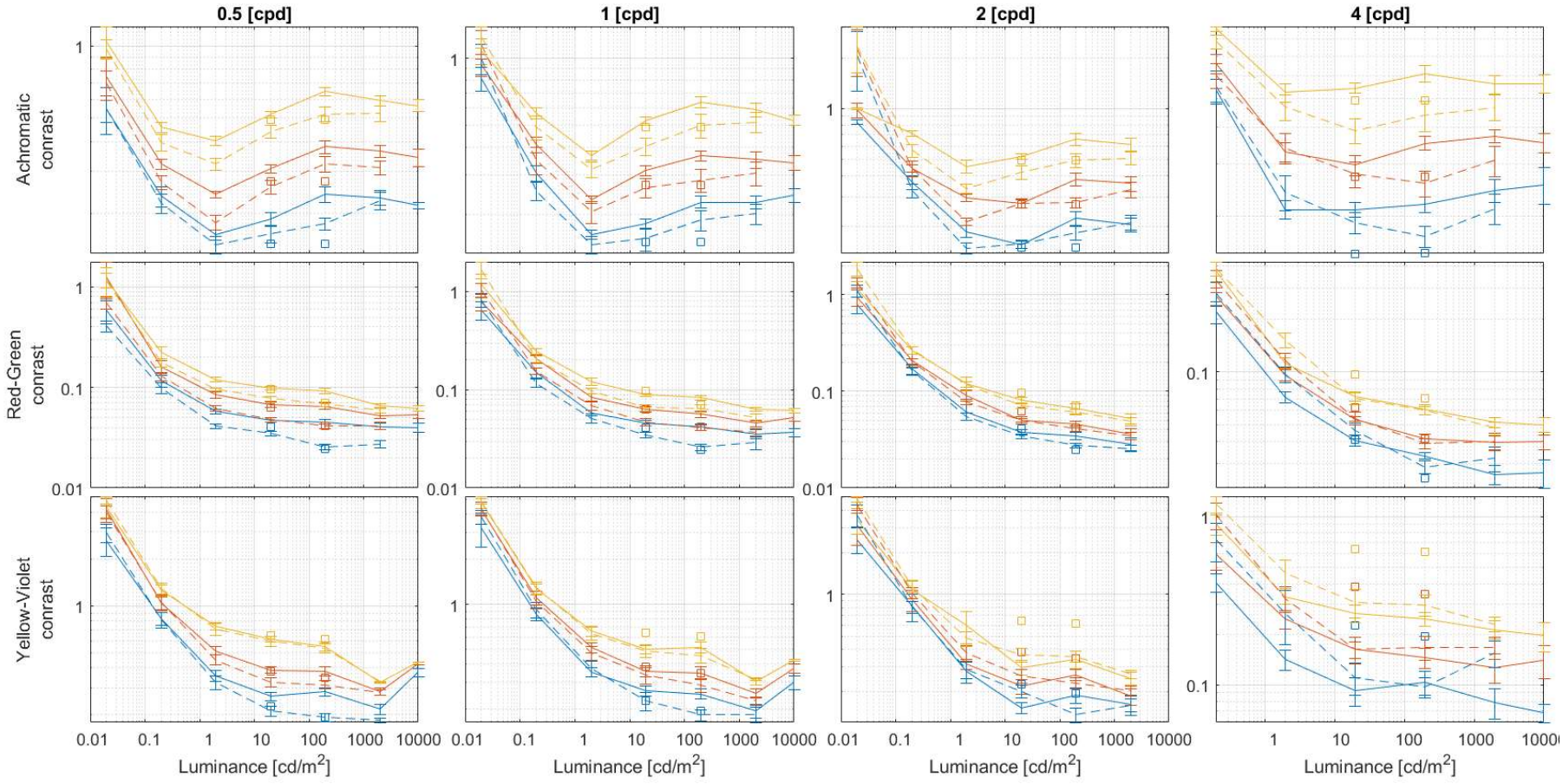
Test  Reference

Results: lines of matching contrast



N=9 or 14

Results: lines of matching contrast



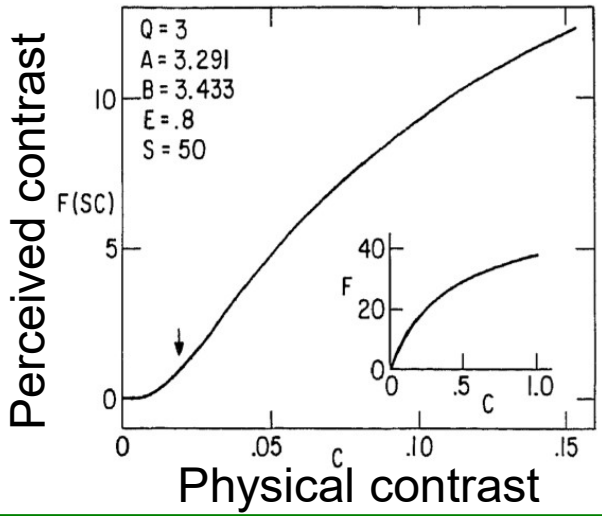
Supra-threshold contrast matching

Contrast transducer

- [Wilson 1980]
- Indirect measurement
- Over-predicts perceived contrast loss at low luminance

Kulikowski's model

- [Kulikowski 1976]
- Direct measurements
- Well predicts some of contrast matching data



Contrast at luminance A

Detection threshold at luminance A

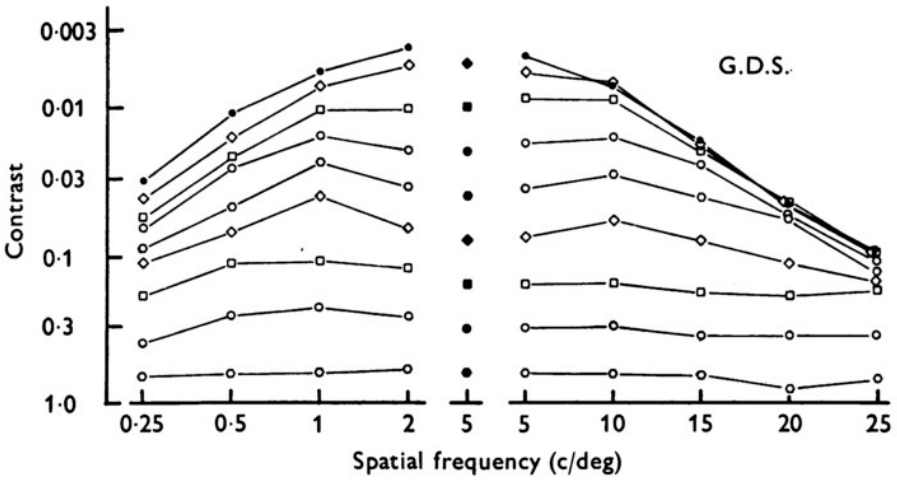
$$C - C_t = \tilde{C} - \tilde{C}_t$$

Contrast at luminance B

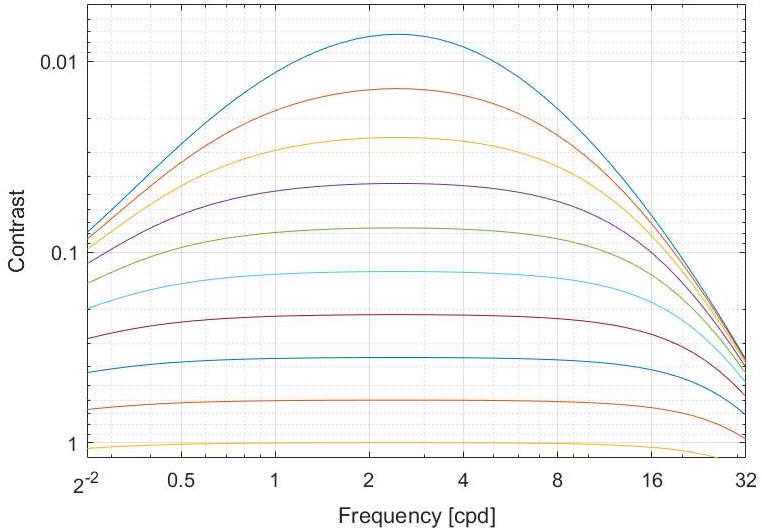
Detection threshold at luminance B

Predicting contrast constancy

Georgeson & Sullivan's data

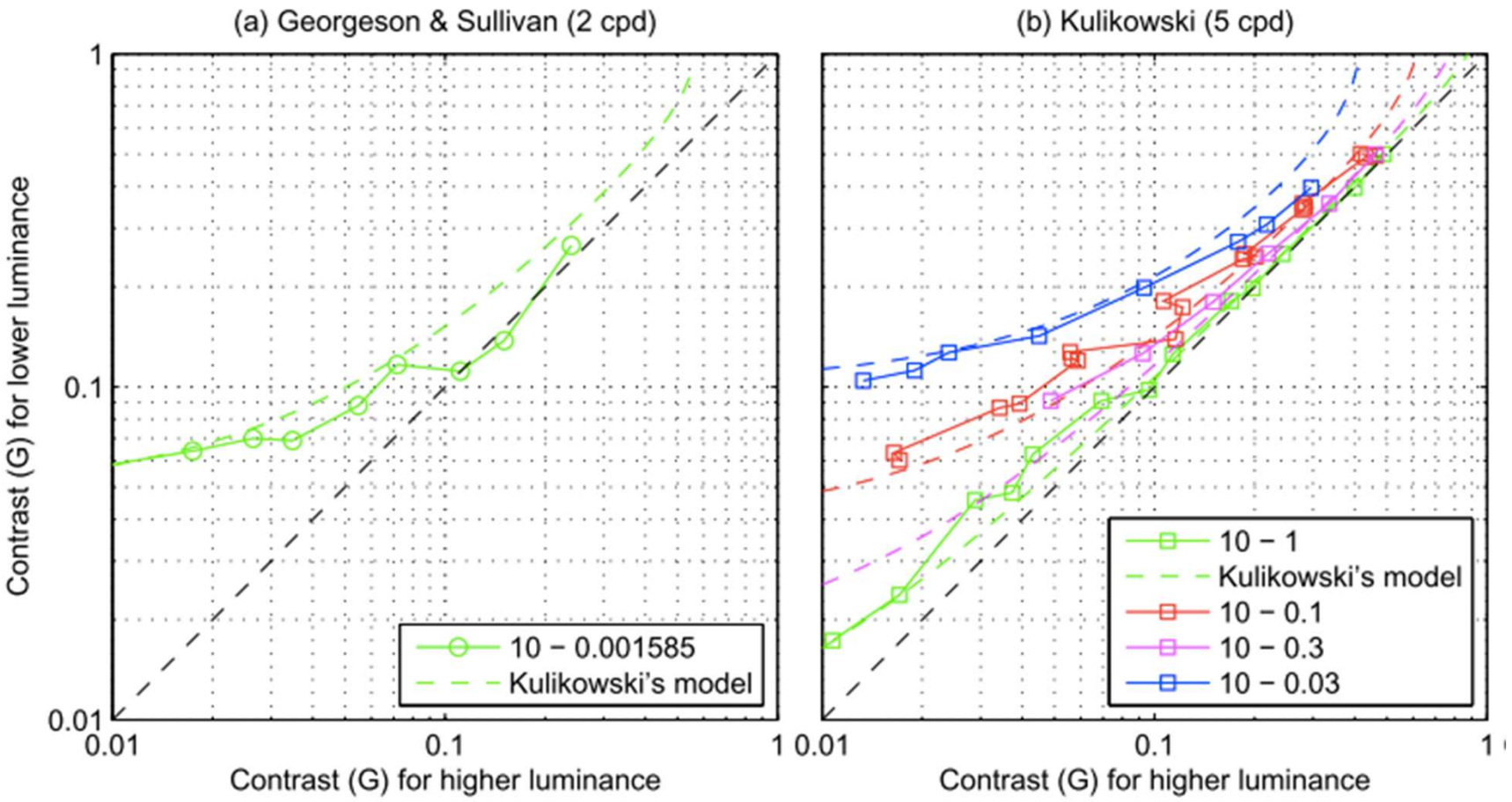


Kulikowski's model based on OmniCSF



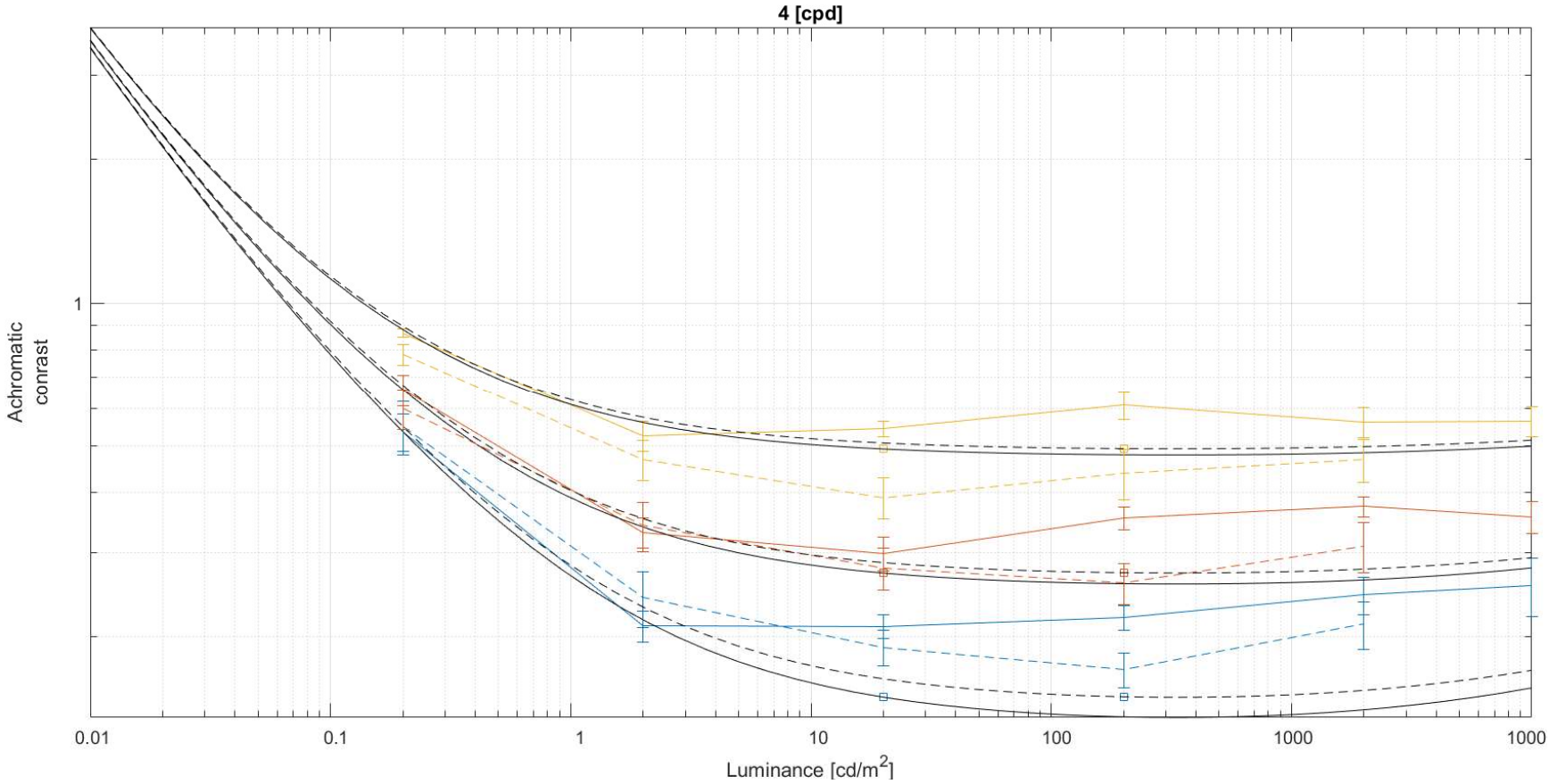
$$C(\rho) = C(\rho_{ref}) - C_T(\rho_{ref}) + C_T(\rho)$$

Predicting data with the model



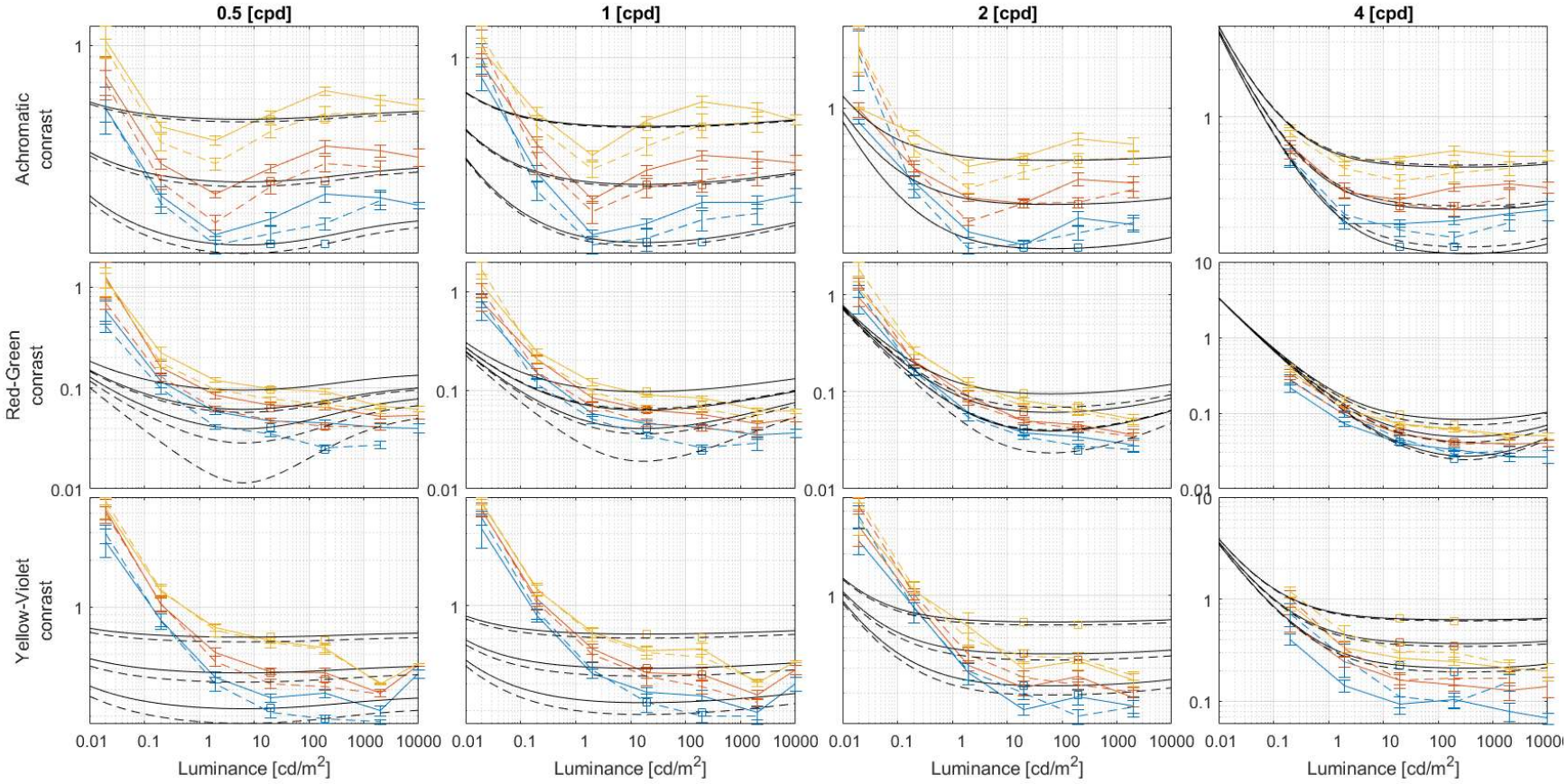
Predictions for our data

- Kulikowski's model works well for high frequencies



Predictions for our data

- And not so well for lower frequencies



Simulating and compensating for night vision

WANAT, R. AND MANTIUK, R.K. 2014.
ACM Transactions on Graphics (Proc. of SIGGRAPH) 33, 4, 147.

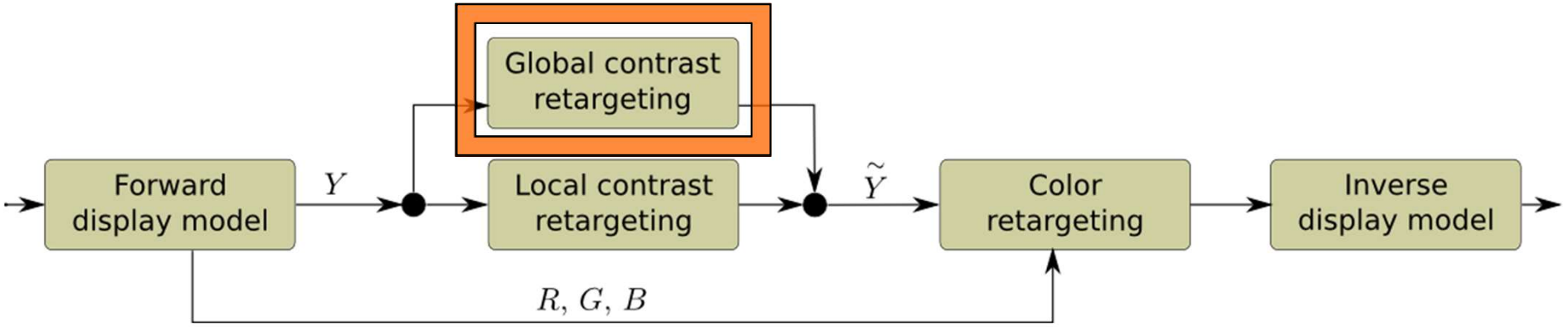
Image appearance at low light

- Reduced global contrast & brightness

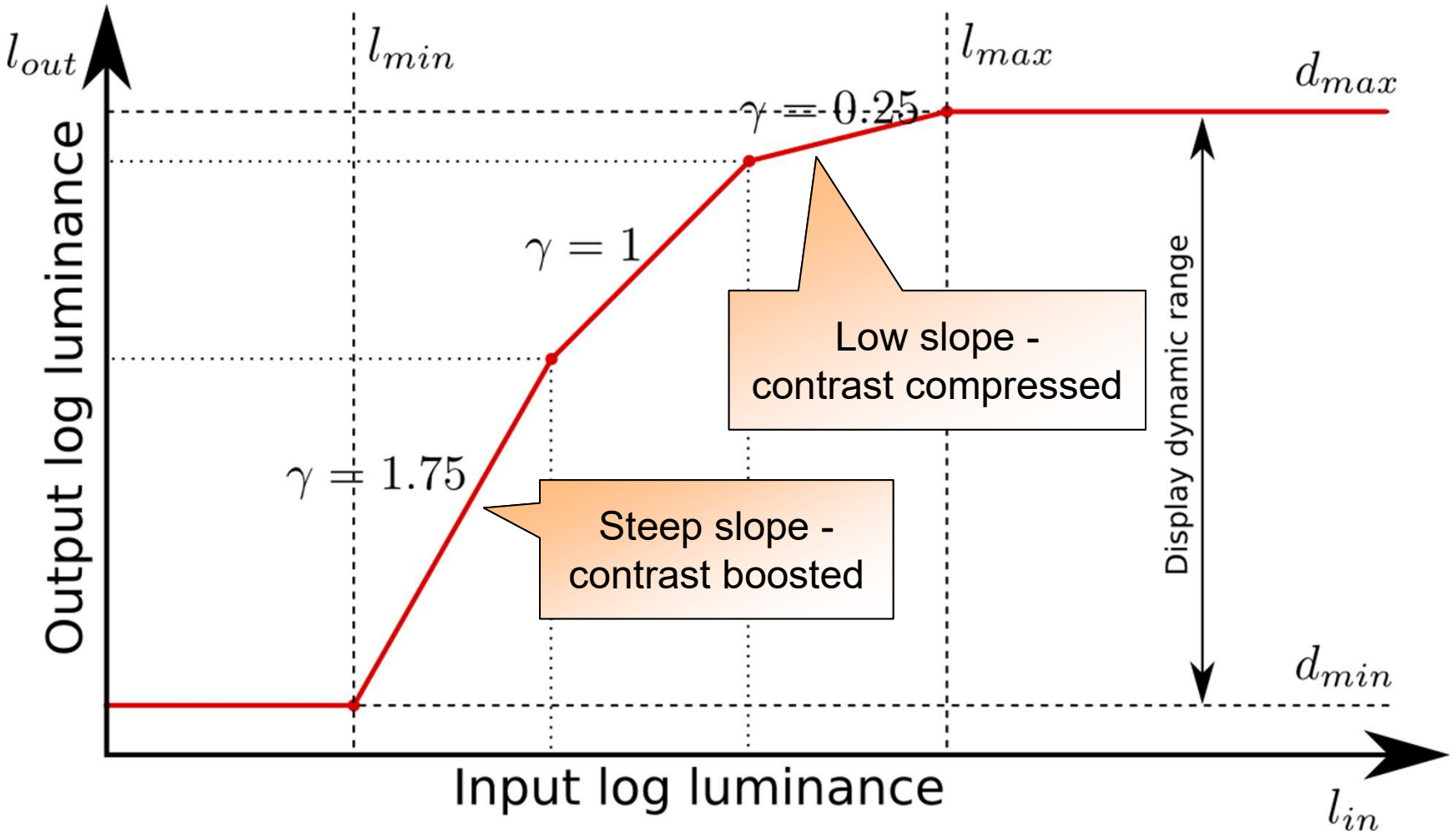
- Reduced local contrast
  - Small details disappear

- Changes in color
  - Blue shift
  - Reduced color saturation

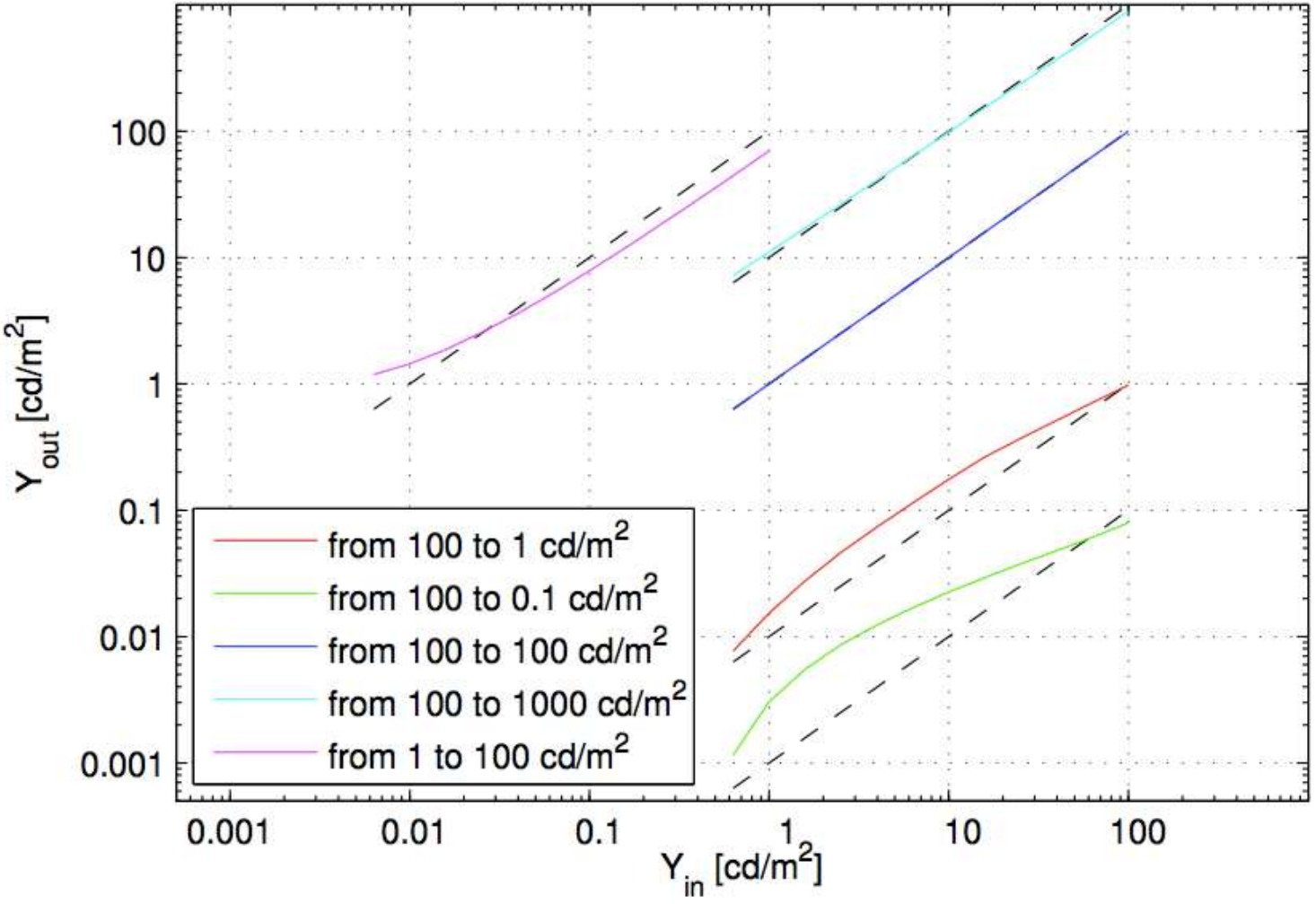
The algorithm



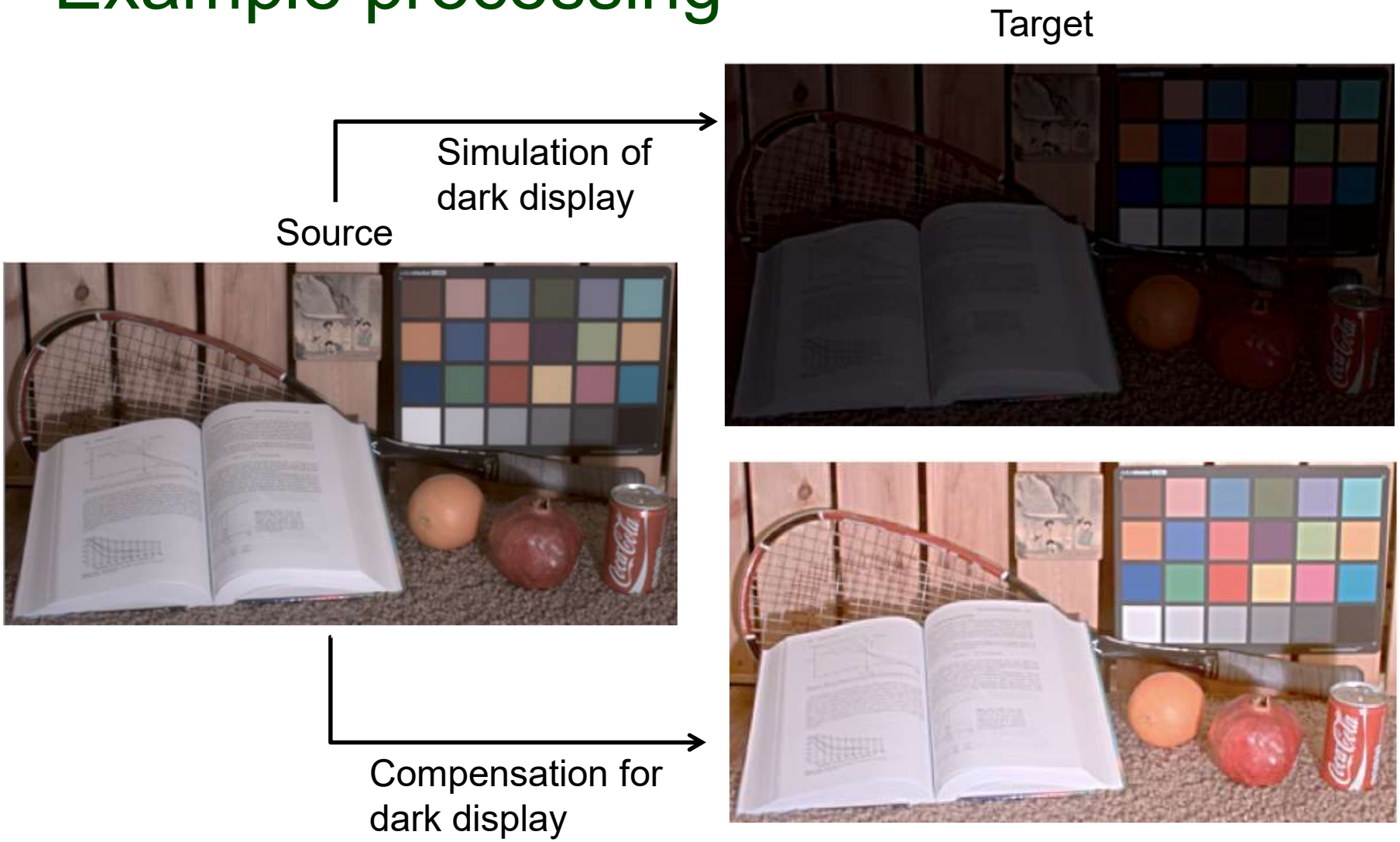
Global contrast - tone curve



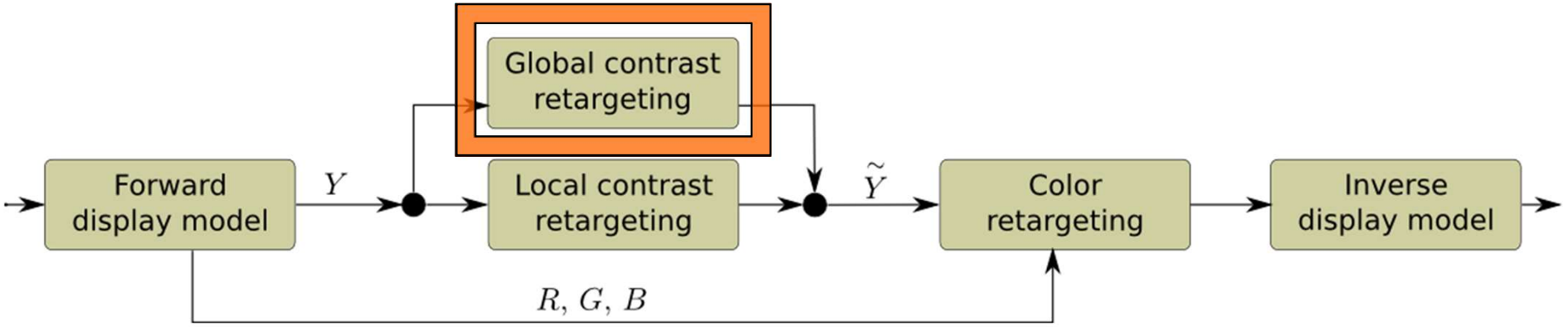
Examples of tone-curves



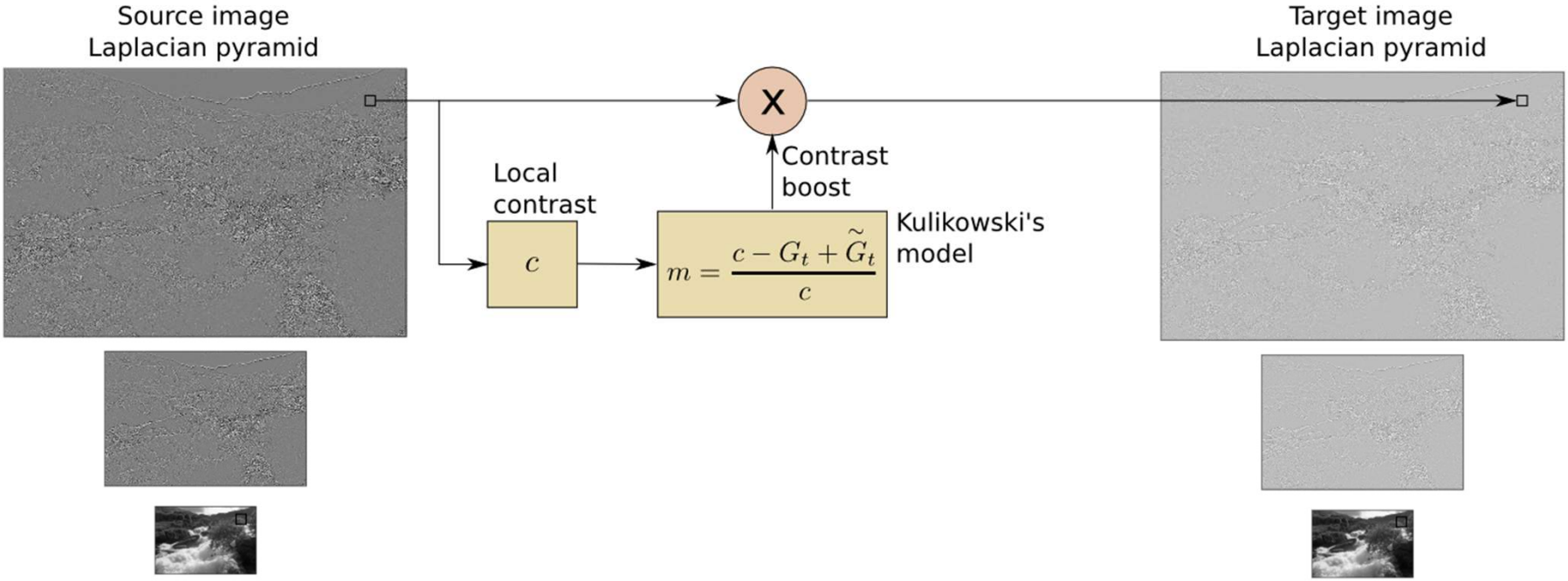
Example processing



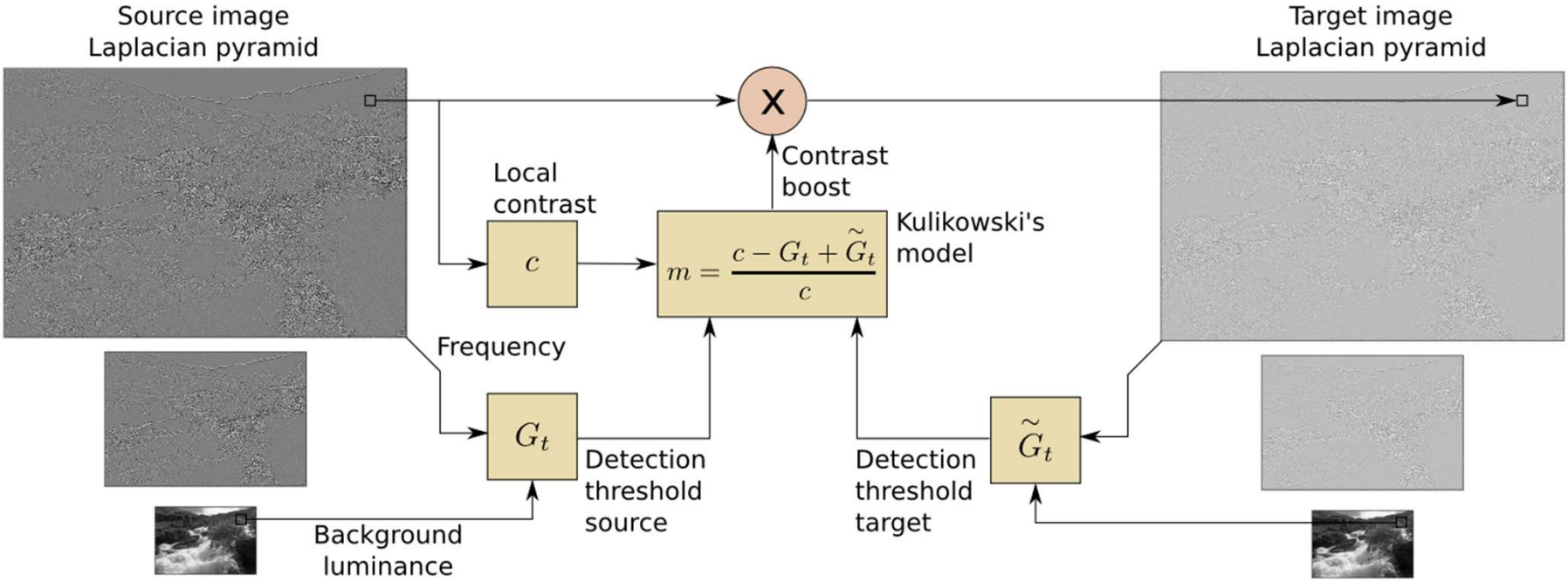
The algorithm



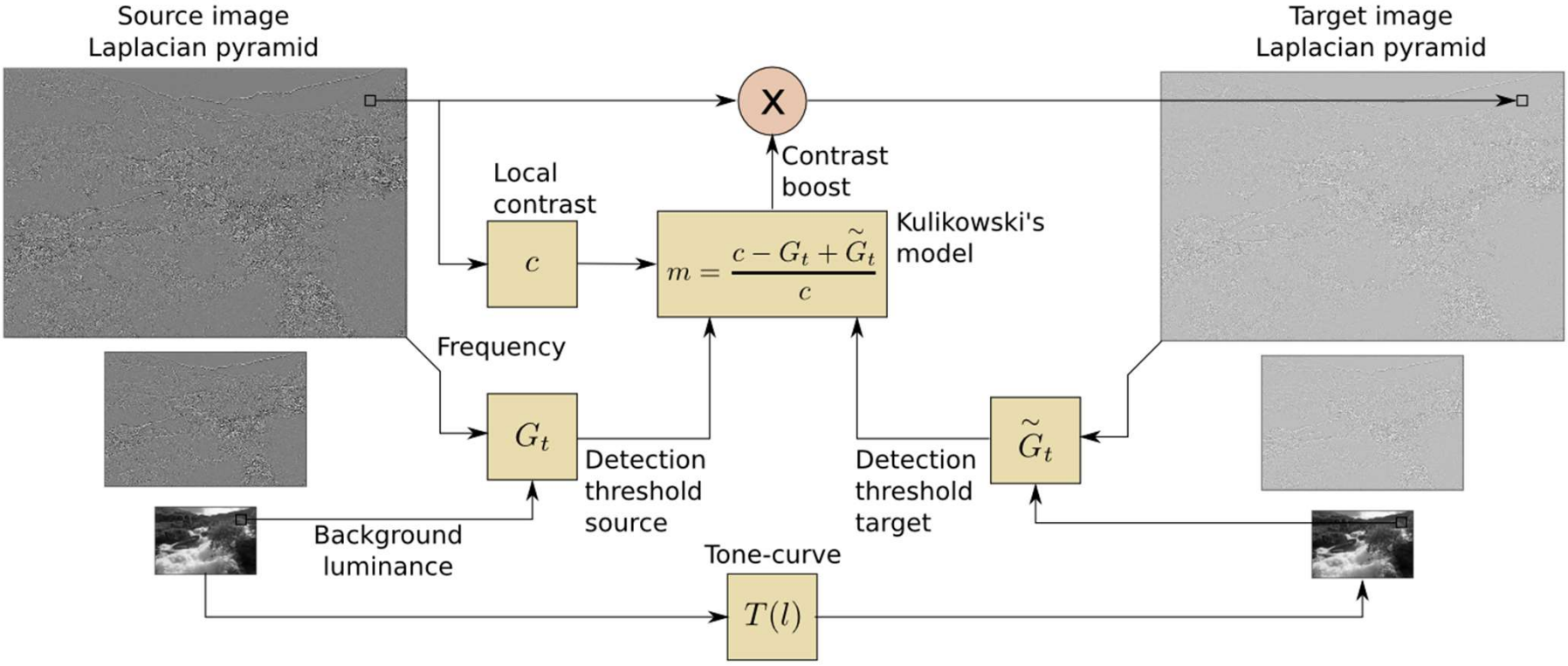
Local contrast processing



Local contrast processing



Local contrast processing



Example processing

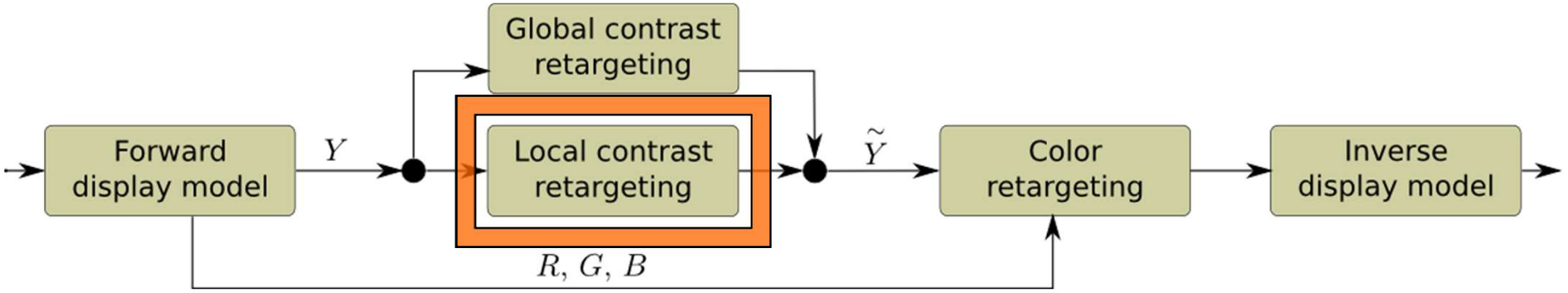
Target

Simulation of dark display

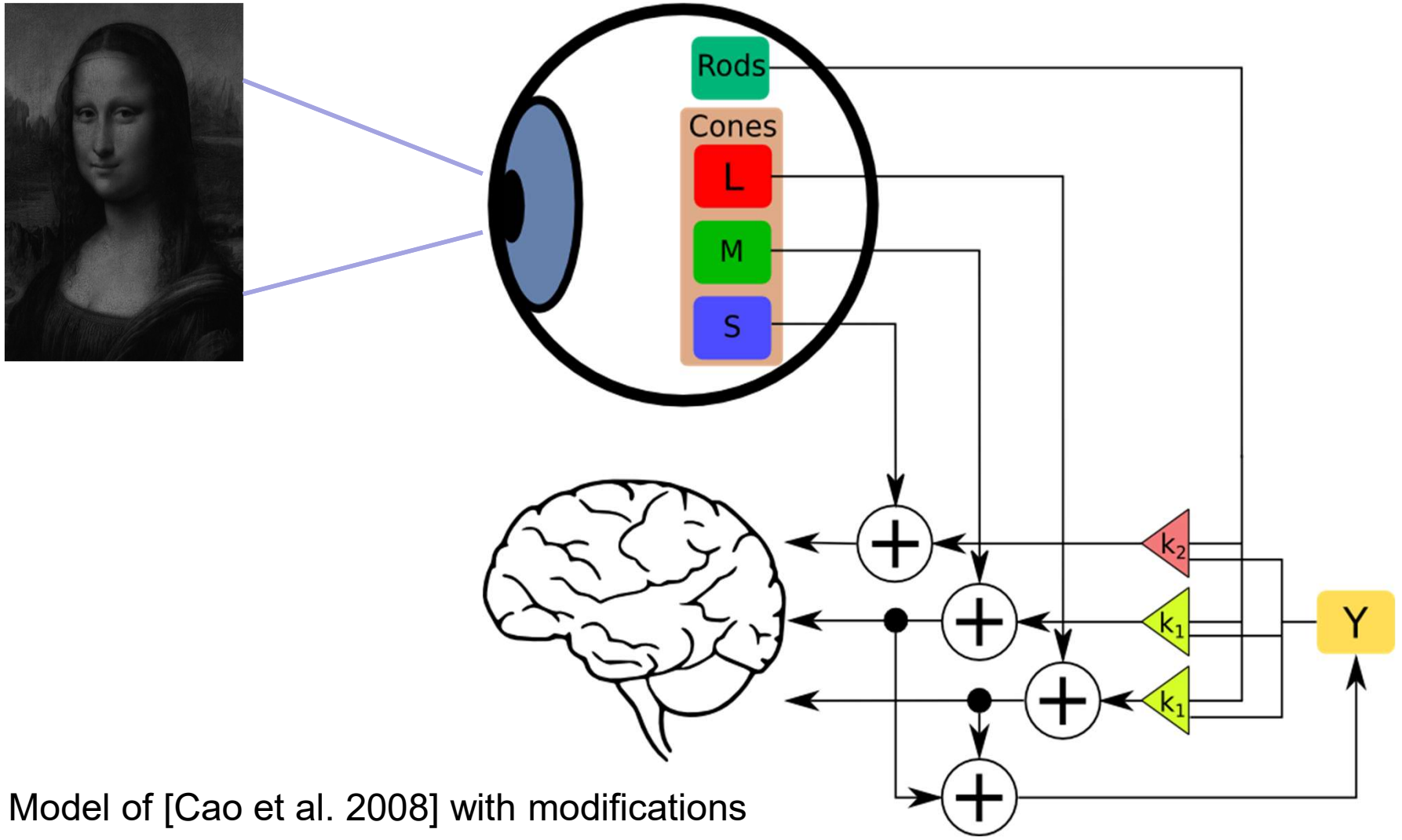
Source

Compensation for dark display

The algorithm



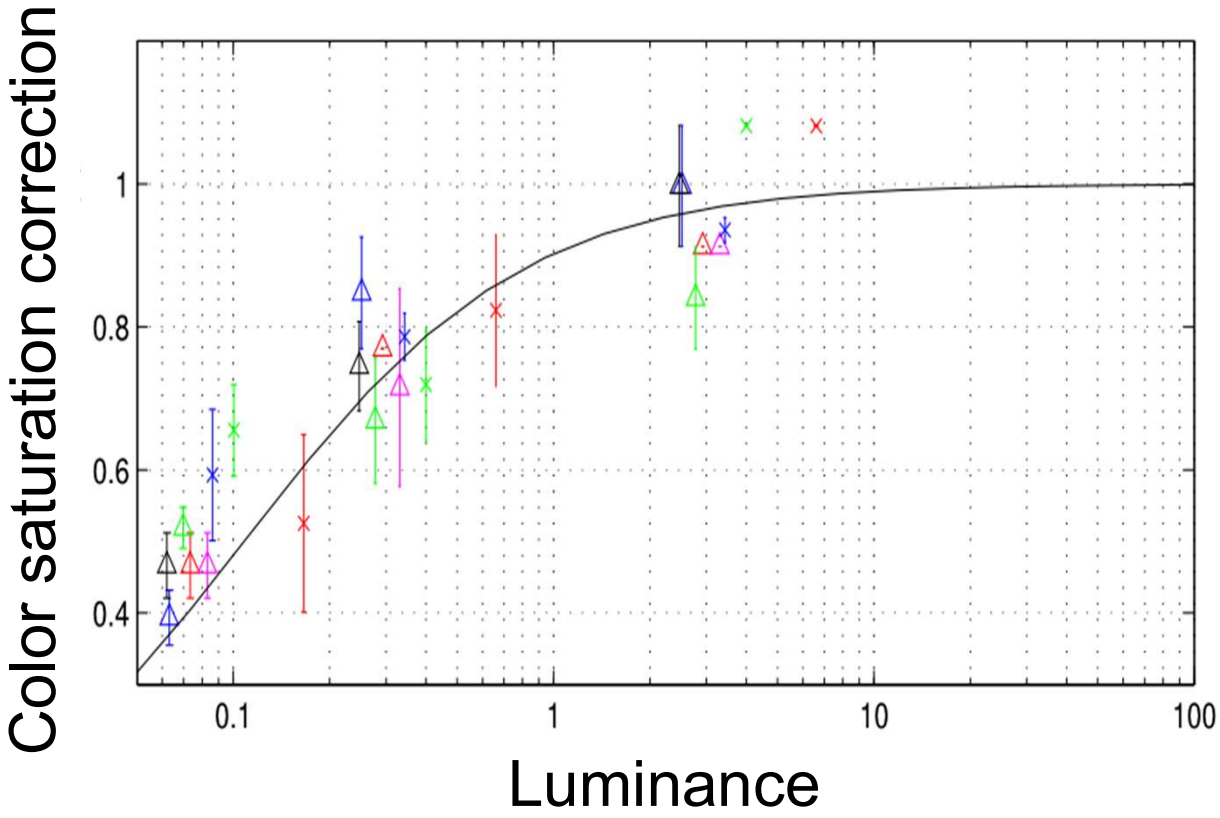
Colour perception at the mesopic luminance



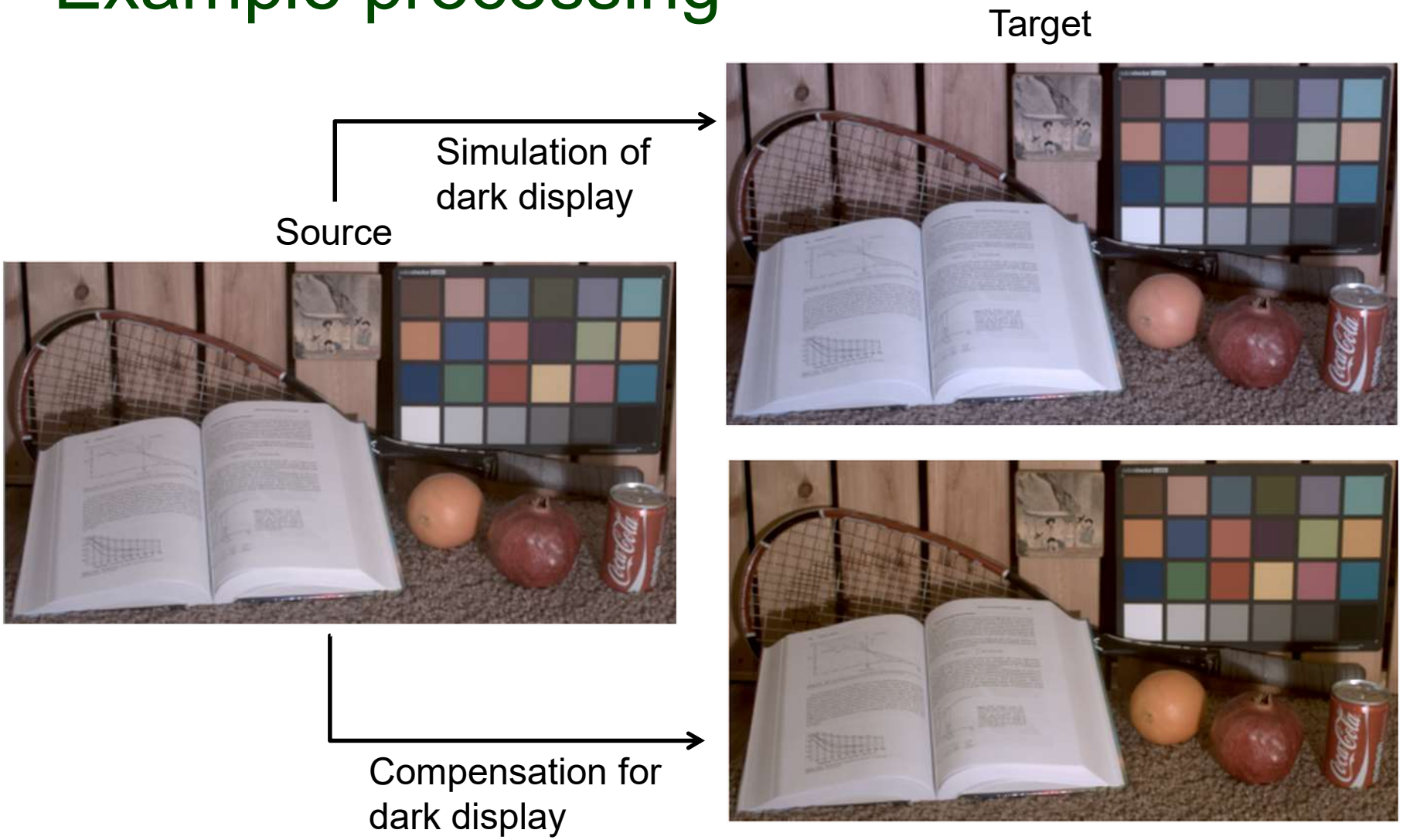
Model of [Cao et al. 2008] with modifications

Saturation matching experiment

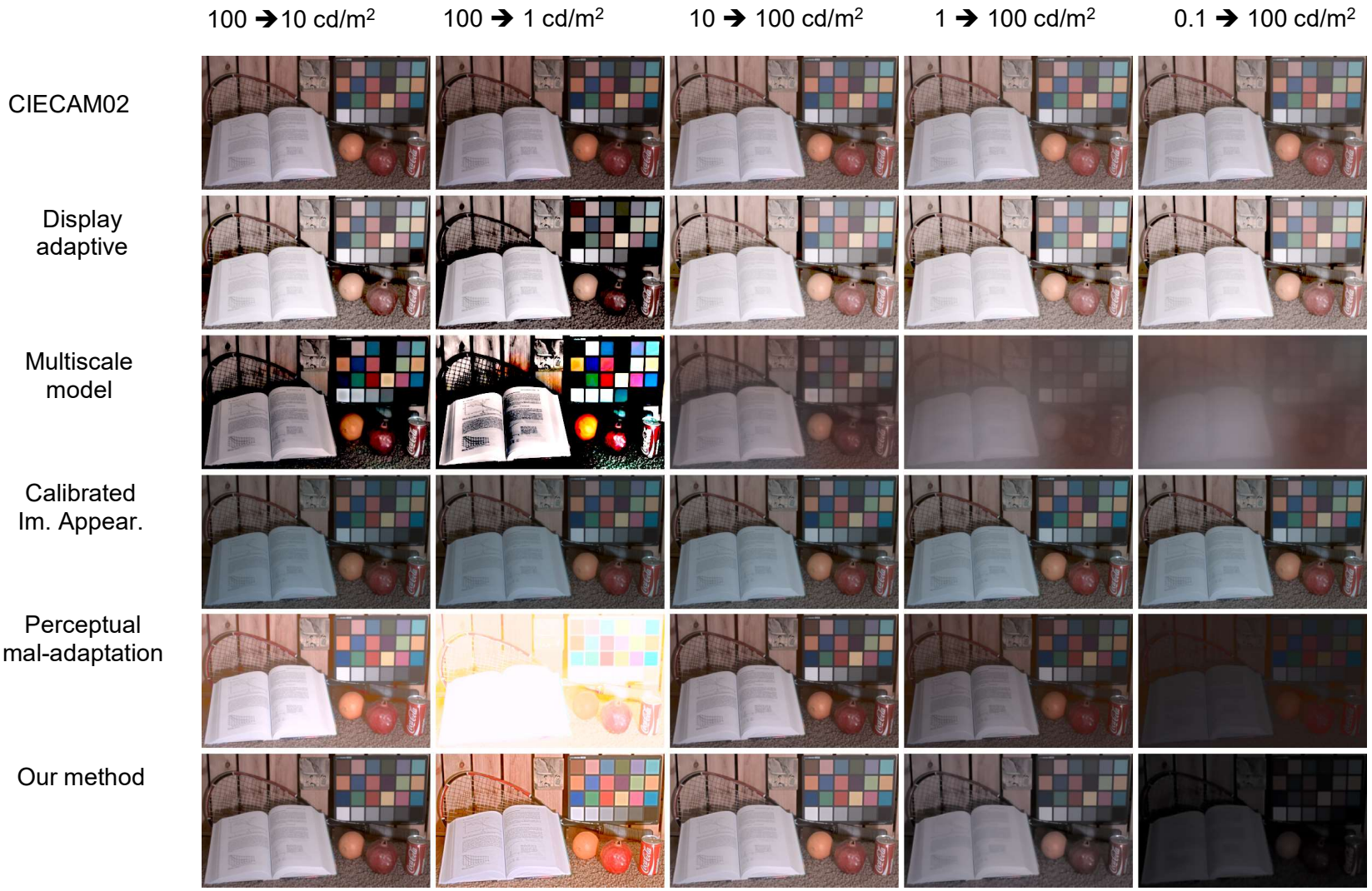
- Each eye adapted to different luminance
- Reference image at 200 cd/m^2



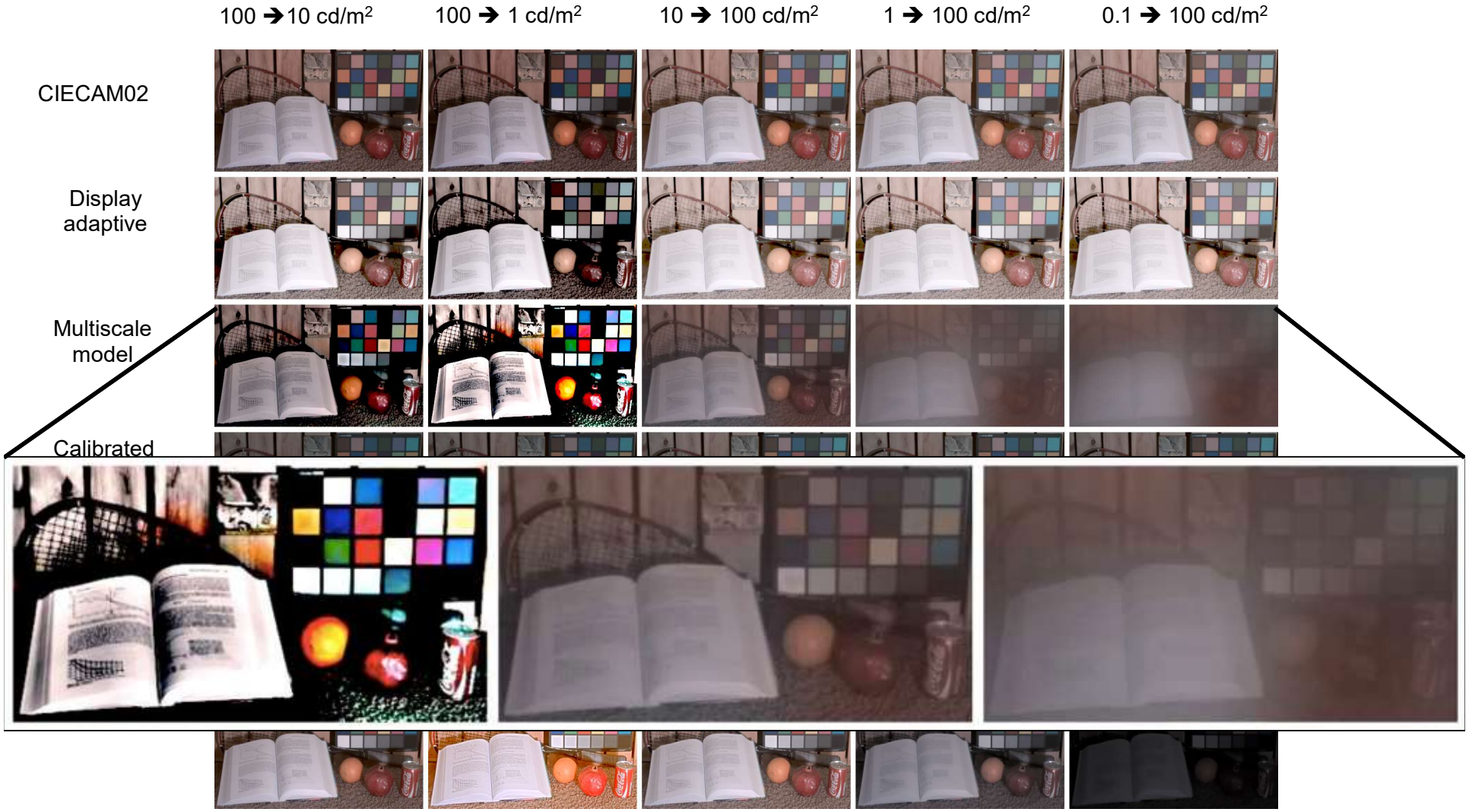
Example processing



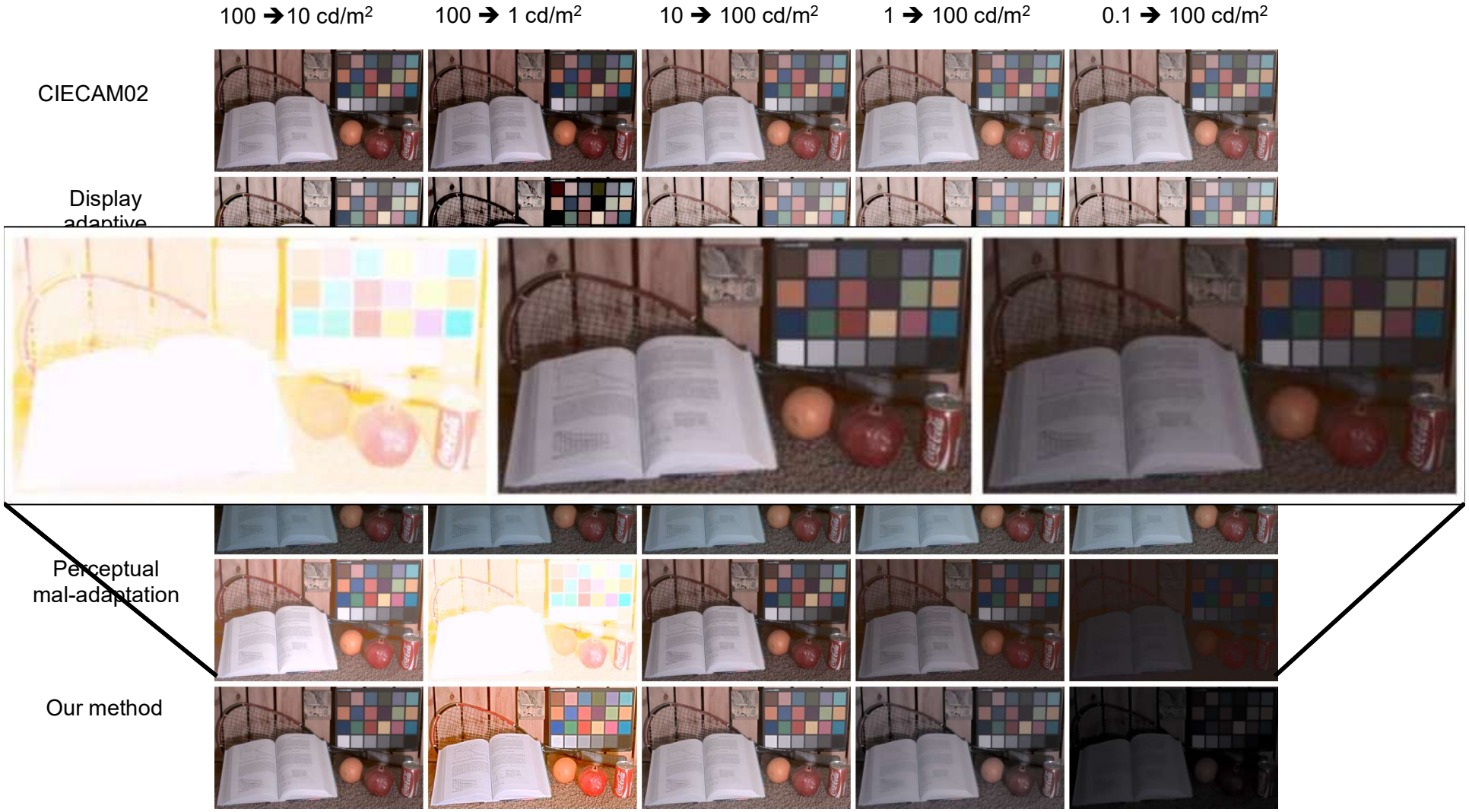
Comparison with other algorithms



Comparison with other algorithms



Comparison with other algorithms



Original

Kirk & O'Brien

Original

Our method

Age-adaptive night vision

Video 4

Rivoli

Simulation of age-adaptive night vision

Is the problem solved?

- Still a few challenges ahead
  - The reproduction of colour could be better
    - We hope OmniCSF and our latest data can help
  - We also want the compensation for the
    - viewing distance
    - age
  - Compensation is not always possible
    - When compensated colours exceed the dynamic range
    - How to design displays that offer a better compensation?

Commercialization vs public domain

- The method was licensed to a start-up company
  - Later acquired by a bigger company in automotive sector
- [Good] The method is now deployed to automotive displays in 100,000s of cars
  - To make displays more legible in sunlight
  - and at night driving
- [Bad] But it could be more widely applied in mobile displays
  - Open Source code can sometimes make a bigger impact than $M invested

Summary

- OmniCSF
- And its applications
  - PU encoding for quality metrics
  - Pre-filtering for coding
- Contrast matching
- Simulation and compensation for night vision