SIGGRAPH ASIA 2018 TOKYO

Rafał K. Mantiuk

HDR, displays & low-level vision

SIGGRAPH Asia Course on Cutting-Edge VR/AR Display Technologies

UNIVERSITY OF CAMBRIDGE

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These slides are a part of the course

Cutting-edge VR/AR Display Technologies (Gaze-, Accommodation-, Motion-aware and HDR-enabled)

Presented at SIGGRAPH Asia in Tokyo on the 5th of December 2018

The latest version of the slides and the slides for the remaining part of the tutorial can be found at:

https://github.com/vrdisplays/sigasia2018

HDR & VR ?

- Do we need HDR VR headsets?

http://www.oculusvr.com/

8K HDR

- OLED contrast 1,000,000:1

ToC

- HDR in a nutshell
- Display technologies in VR
- Perception & image quality
- Example: Temporal Resolution Multiplexing

Dynamic range

Dynamic range (contrast)

- As ratio:

$$C = \frac{L_{\max}}{L_{\min}}$$

  - Usually written as C:1, for example 1000:1.

- As "orders of magnitude" or log10 units:

$$C_{10} = \log_{10} \frac{L_{\max}}{L_{\min}}$$

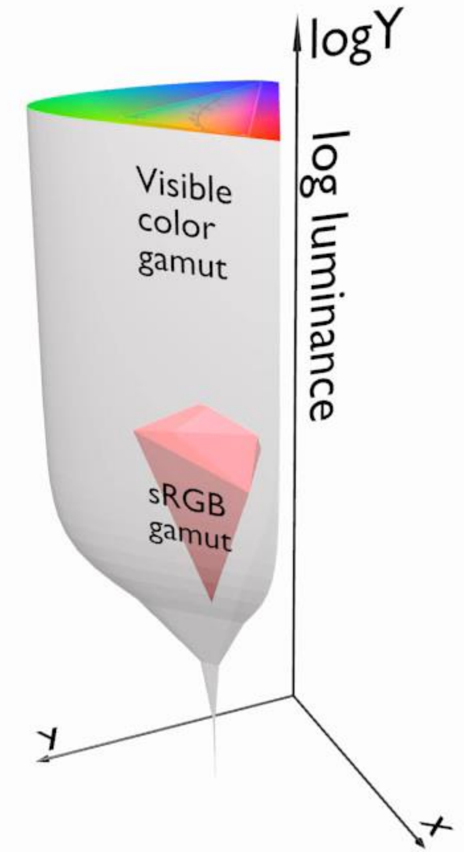
- As stops:

$$C_2 = \log_2 \frac{L_{\max}}{L_{\min}}$$

One stop is doubling of halving the amount of light

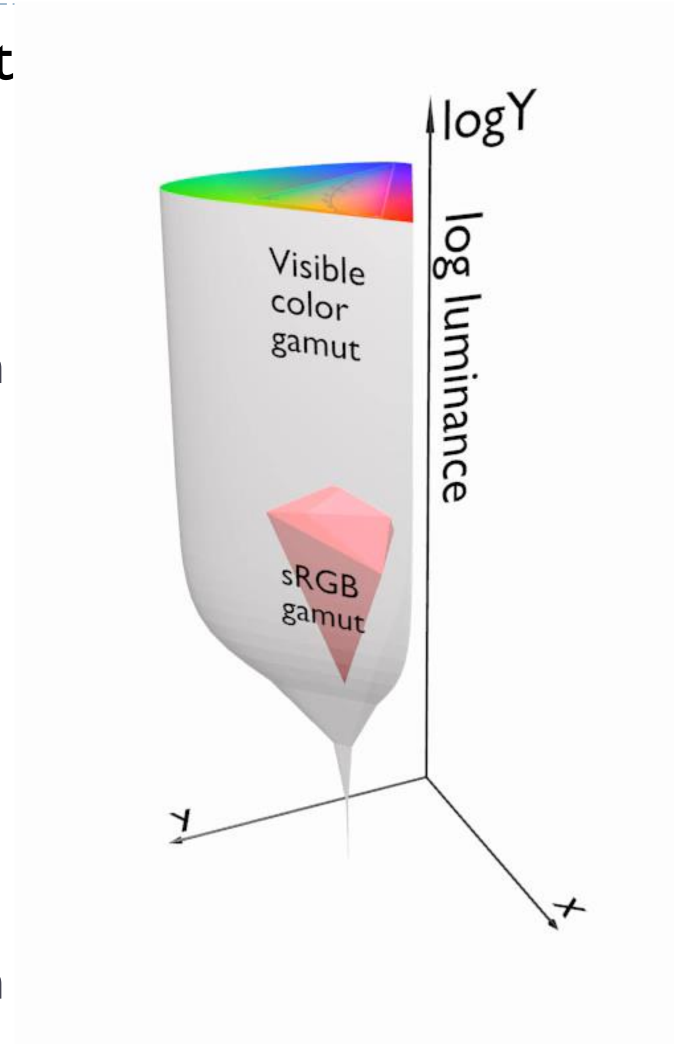
Visible colour gamut

- The eye can perceive more colours and brightness levels than
  - a display can produce
  - a JPEG file can store
- The premise of HDR:
  - Visual perception and not the technology should define accuracy and the range of colours
  - The current standards not fully follow to this principle



Standard vs. High Dynamic Range

- **HDR** cameras/formats/displays attempt capture/represent/reproduce (almost) all visible colours
  - They represent scene colours and therefore we often call this representation *scene-referred*
- **SDR** cameras/formats/devices attempt to capture/represent/reproduce only colours of a standard sRGB colour gamut, mimicking the capabilities of CRTs monitors
  - They represent display colours and therefore we often call this representation *display-referred*



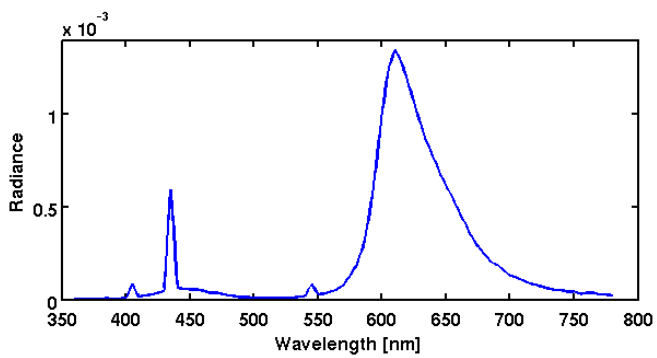
Luminance

- Luminance – measure of light intensity weighted by the sensitivity of the achromatic mechanism. Units: cd/m^2

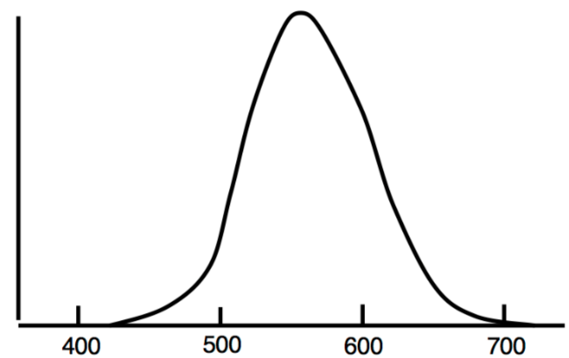
Luminance

$$L_V = \int_{350}^{700} kL(\lambda)V(\lambda)d\lambda \qquad k = \frac{1}{683.002}$$

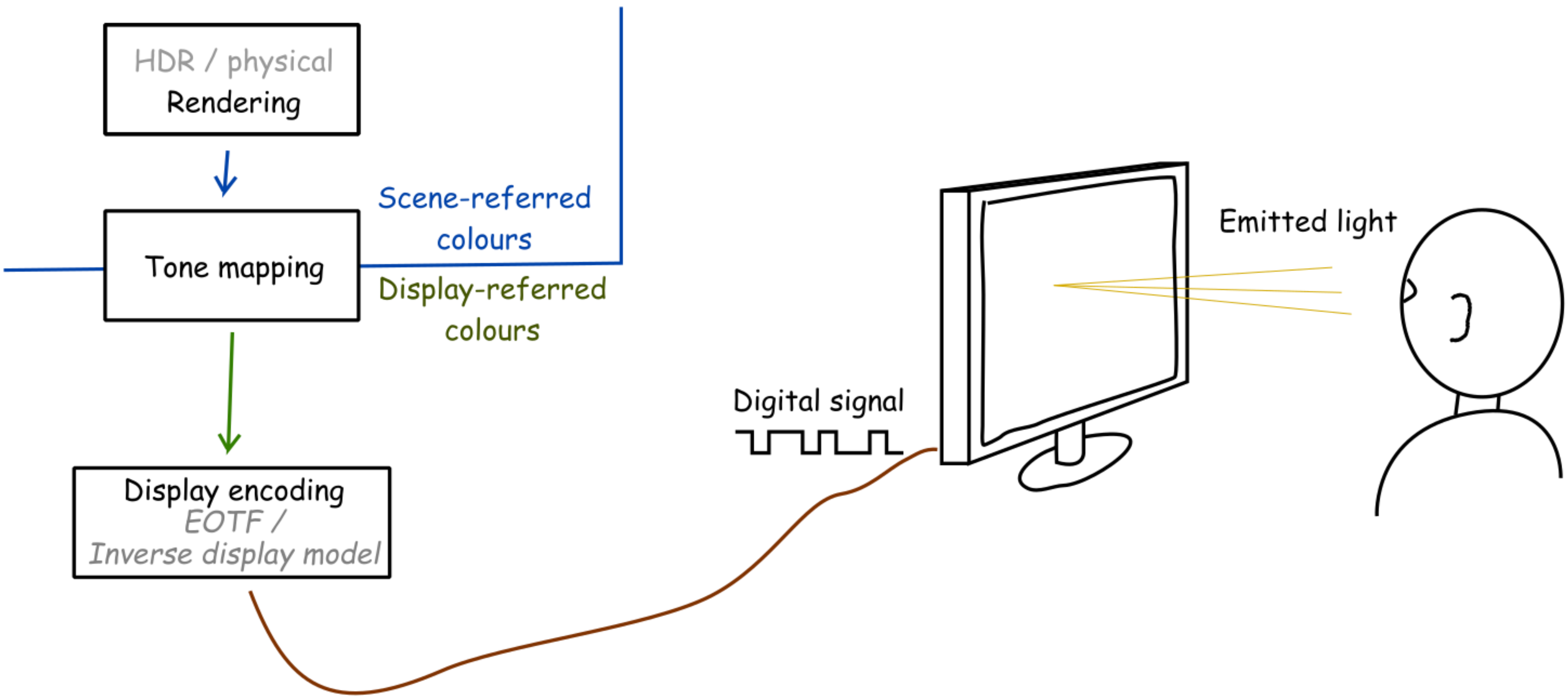
Light spectrum (radiance)



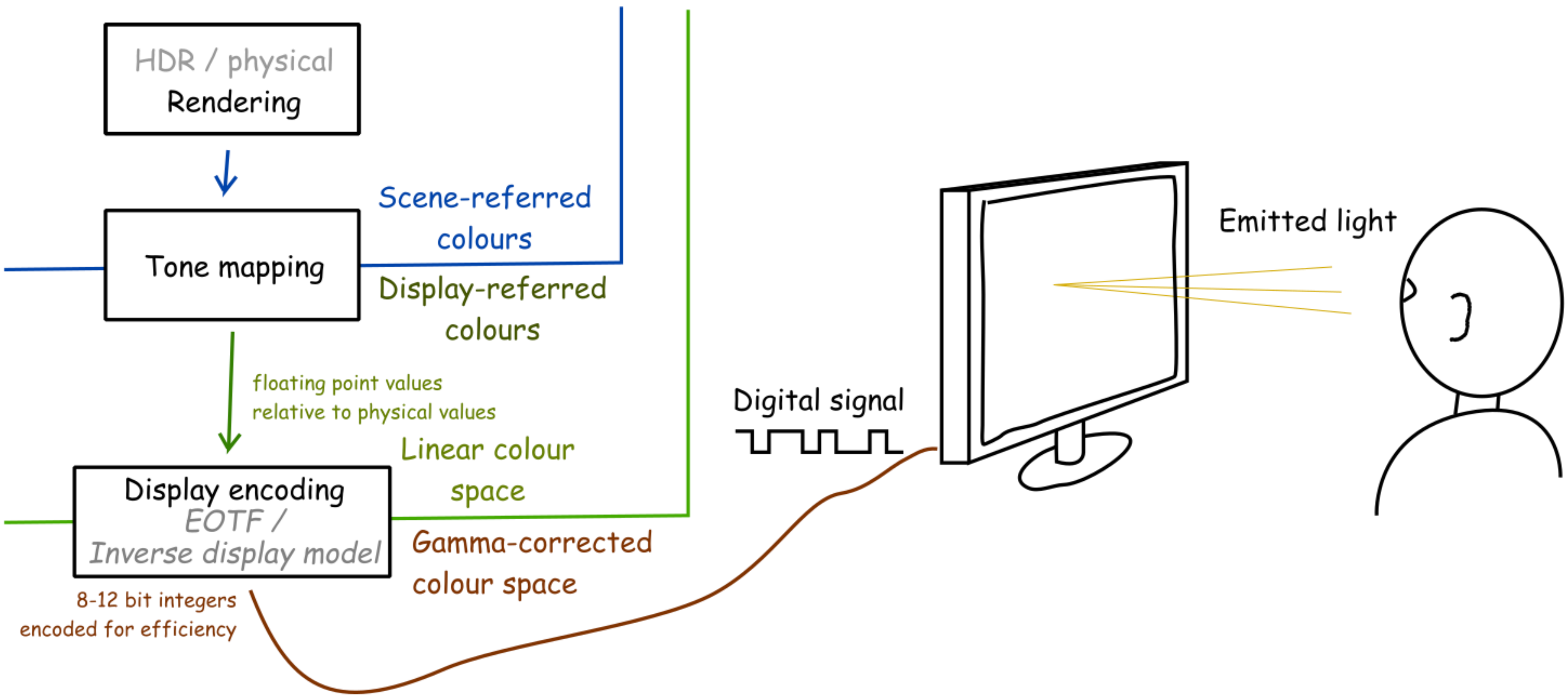
Luminous efficiency function (weighting)



From rendering to display



From rendering to display



Luminance and Luma

- Luminance
  - Photometric quantity defined by the spectral luminous efficiency function
- $L \approx 0.2126\,R + 0.7152\,G + 0.0722\,B$
- Units: cd/m^2

- Luma
  - Gray-scale value computed from LDR (gamma corrected) image
- $Y = 0.2126\,R' + 0.7152\,G' + 0.0722\,B'$
  - R' – prime denotes gamma correction

$$R' = R^{1/g}$$

- Unitless

Sensitivity to luminance

- Weber-law – the just-noticeable difference is proportional to the magnitude of a stimulus

Ernst Heinrich Weber
[From wikipedia]

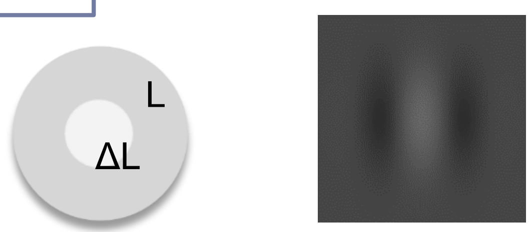
$$\frac{\Delta L}{L} = k$$

The smallest detectable luminance difference → ΔL

Background (adapting) luminance → L

Constant → k

Typical stimuli:



Consequence of the Weber-law

- Smallest detectable difference in luminance

$$\frac{\Delta L}{L} = k$$

For k=1%

L	ΔL
100 cd/m^2	1 cd/m^2
1 cd/m^2	0.01 cd/m^2

- Adding or subtracting luminance will have different visual impact depending on the background luminance
- Unlike LDR luma values, luminance values are **not** perceptually uniform!

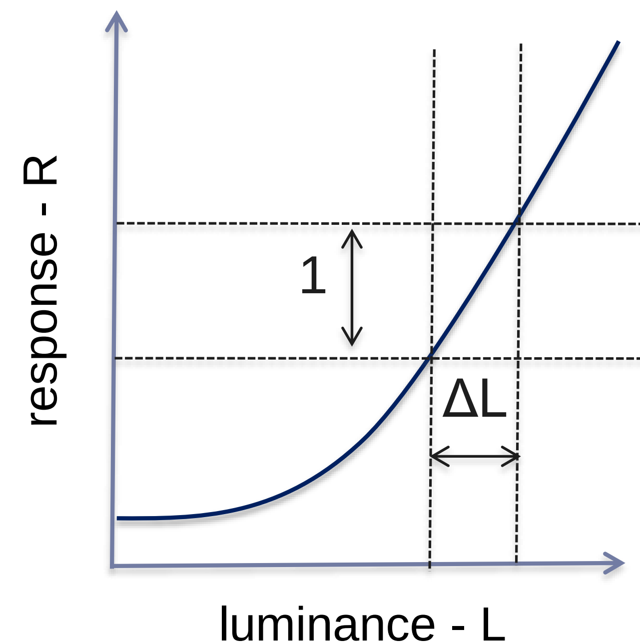
How to make luminance (more) perceptually uniform?

- Using "Fechnerian" integration

$$\frac{dR}{dl}(L) = \frac{1}{\Delta L(L)}$$

Derivative of response

Detection threshold



Luminance transducer:

$$R(L) = \int_0^L \frac{1}{\Delta L(l)}\, dl$$

Assuming the Weber law

$$\frac{\Delta L}{L} = k,$$

- and given the luminance transducer

$$R(L) = \int_0^L \frac{1}{\Delta L(l)} dl$$

- the response of the visual system to light is:

$$R(L) = \int \frac{1}{kL} dL = \frac{1}{k} \ln(L) + k_1$$

Fechner law

$$R(L) = a \ln(L)$$

- Response of the visual system to luminance is **approximately** logarithmic

- The values of HDR pixel values are much more intuitive when they are plotted / considered / processed in the logarithmic domain

Gustav Fechner
[From Wikipedia]

ToC

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VR display technologies

TFT-LCD *TN, STN, MVA, PVA, IPS*

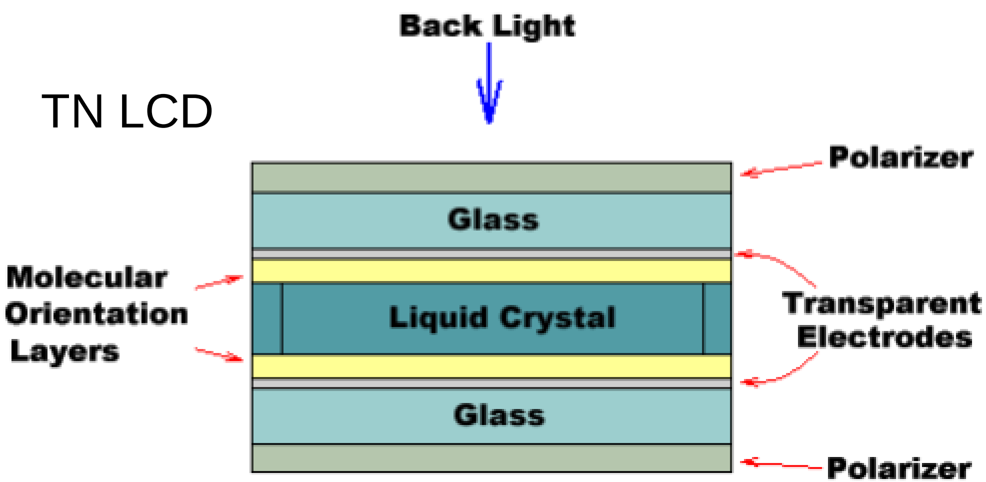
- Contrast: <3000:1
- Transmissive
- Complex temporal response
- Arbitrary bright
- Constant power at constant backlight

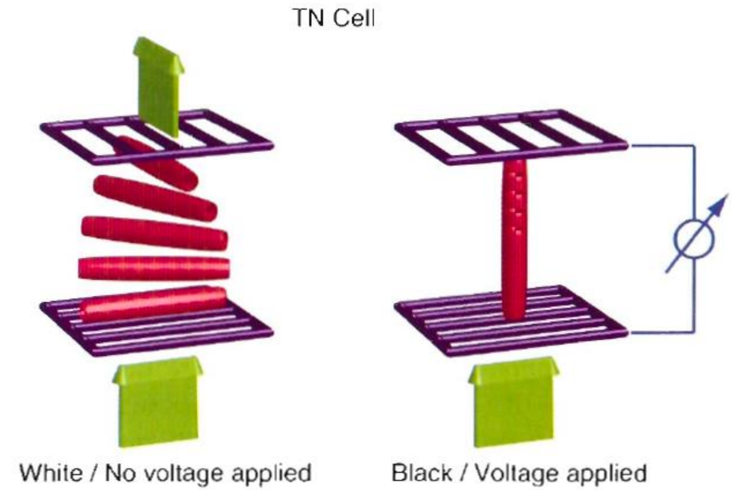
AMOLED

- Contrast: >10,000:1
- Emmisive
- Rapid response
- Brightness affects longevity
- Power varies with image content

LCD

TN LCD

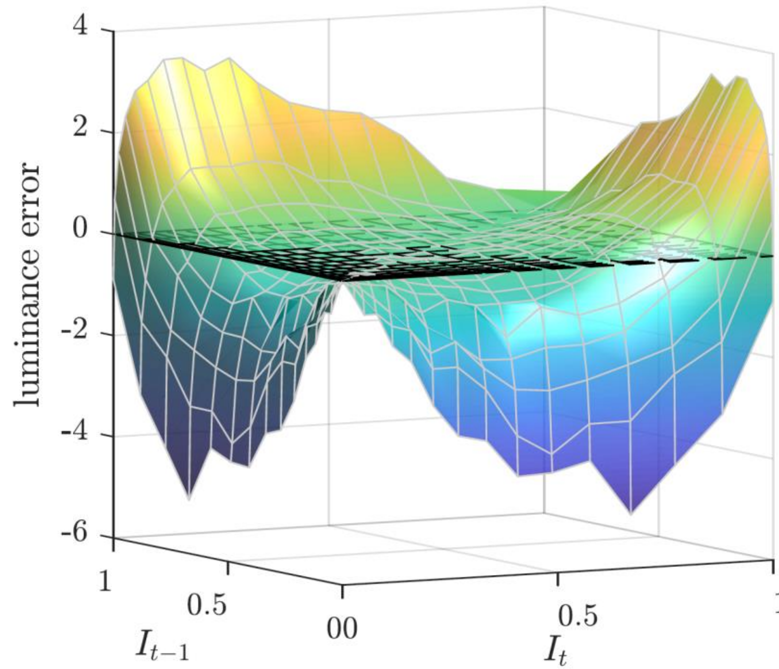


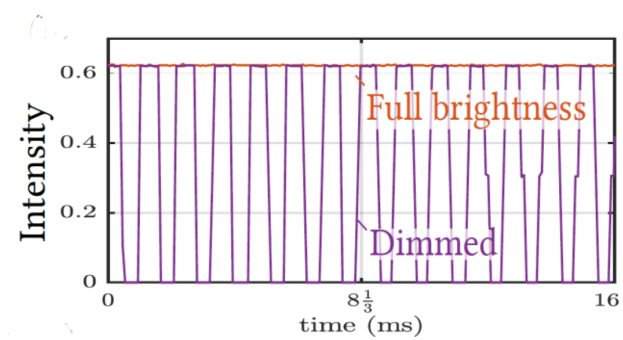


- color may change with the viewing angle
- contrast up to 3000:1
- higher resolution results in smaller fill-factor
- color LCD transmits only up to 8% (more often close to 3-5%) light when set to full white

LCD temporal response

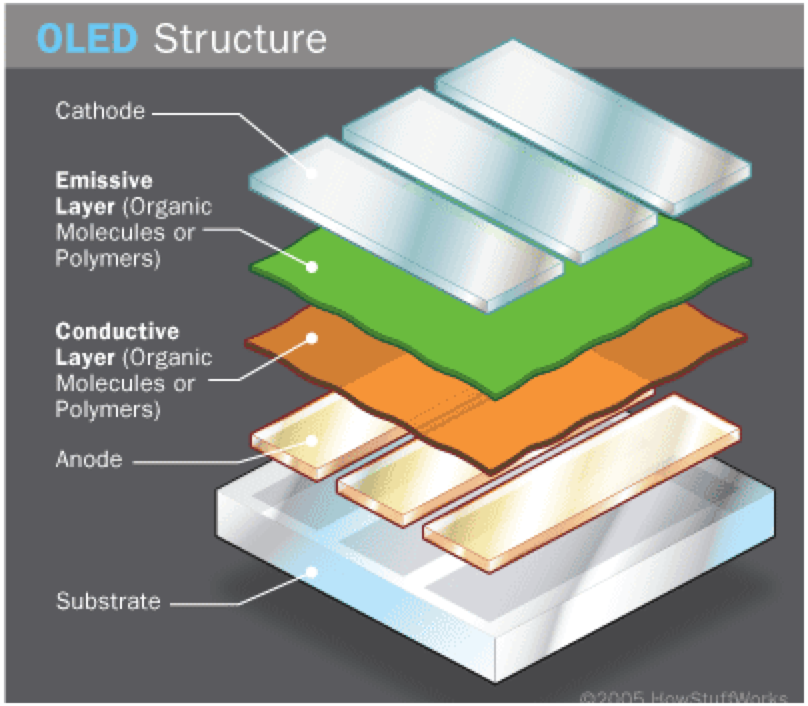
- Experiment on an IPS LCD screen
- We rapidly switched between two intensity levels at 120Hz
- Measured luminance integrated over 1s
- The top plot shows the difference between expected ($\frac{I_{t-1}+I_t}{2}$) and measured luminance
- The bottom plot: intensity measurement for the full brightness and half-brightness display settings





OLED

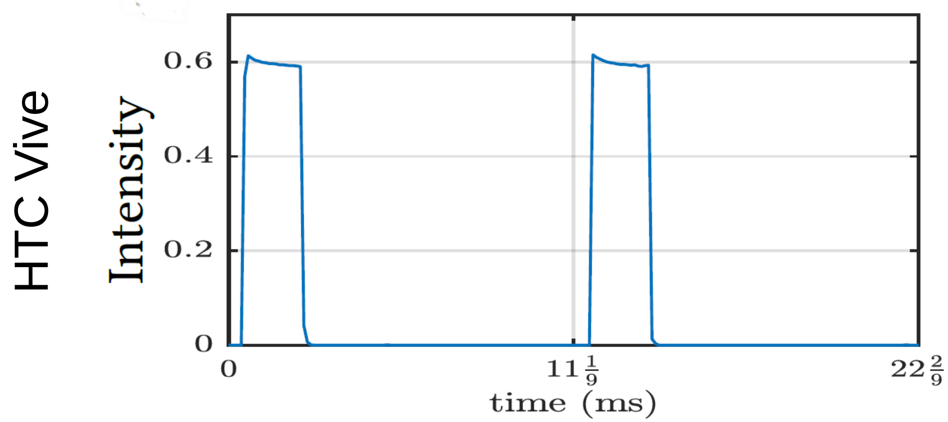
- based on electrophosphorescence
- large viewing angle
- the power consumption varies with the brightness of the image
- fast (< 1 microsec)
- arbitrary sizes

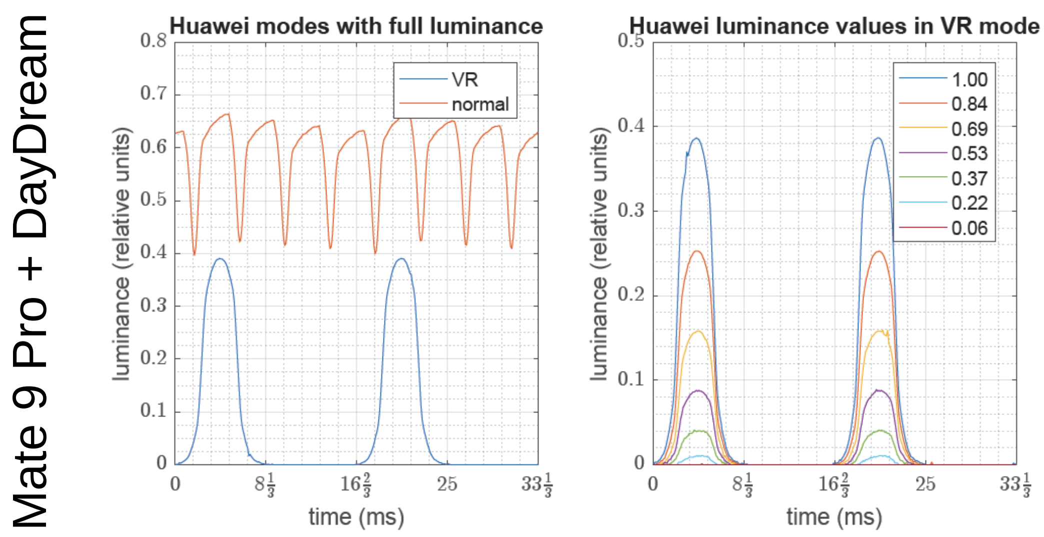


- life-span is a concern
- more difficult to produce

Low persistence displays

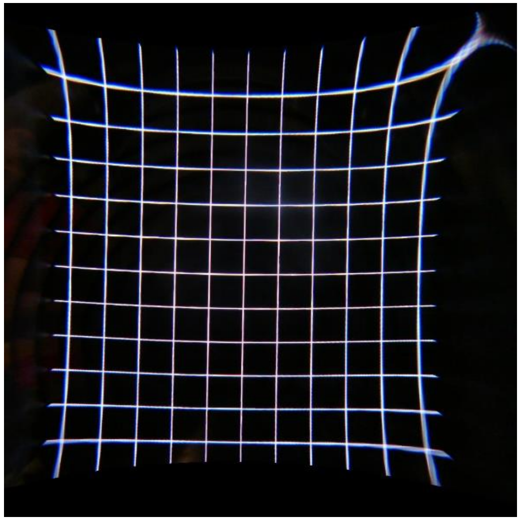
- Most VR displays flash an image for a fraction of frame duration
- This reduces hold-type blur
- And also reduces the perceived lag of the rendering





Lens in VR displays

- Aberrations when viewing off-center
  - Chromatic aberration
  - Loss of resolution
  - Difficult to eliminate if the exact eye position is unknown
- Glare
  - Scattering of the light in the lens
  - From Fresnel fringes
  - Reduces dynamic range



Examples from: http://doc-ok.org/?p=1414

Resolution

- Relevant units: pixels per visual degree [ppd]
- Nyquist frequency in cycles per degree = ½ of ppd
- PC & mobile resolution
  - 1981: 12” 320x200 monitor @50cm: 10.9 ppd
  - 1990: 12” 1024x768 monitor @50cm: 37 ppd
  - 2011: 3.5” 960x640 iPhone @30cm: 68 ppd
  - 2016: 31” 4K monitor @50cm: 50 ppd
  - 2018: 6” phone @30cm: 117 ppd
- VR resolution
  - 2016 HTC Vive: 10 ppd
  - 2018 HTC Vive Pro: 13 ppd

ToC

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(Camera) image reconstruction model

Captured image

Latent image

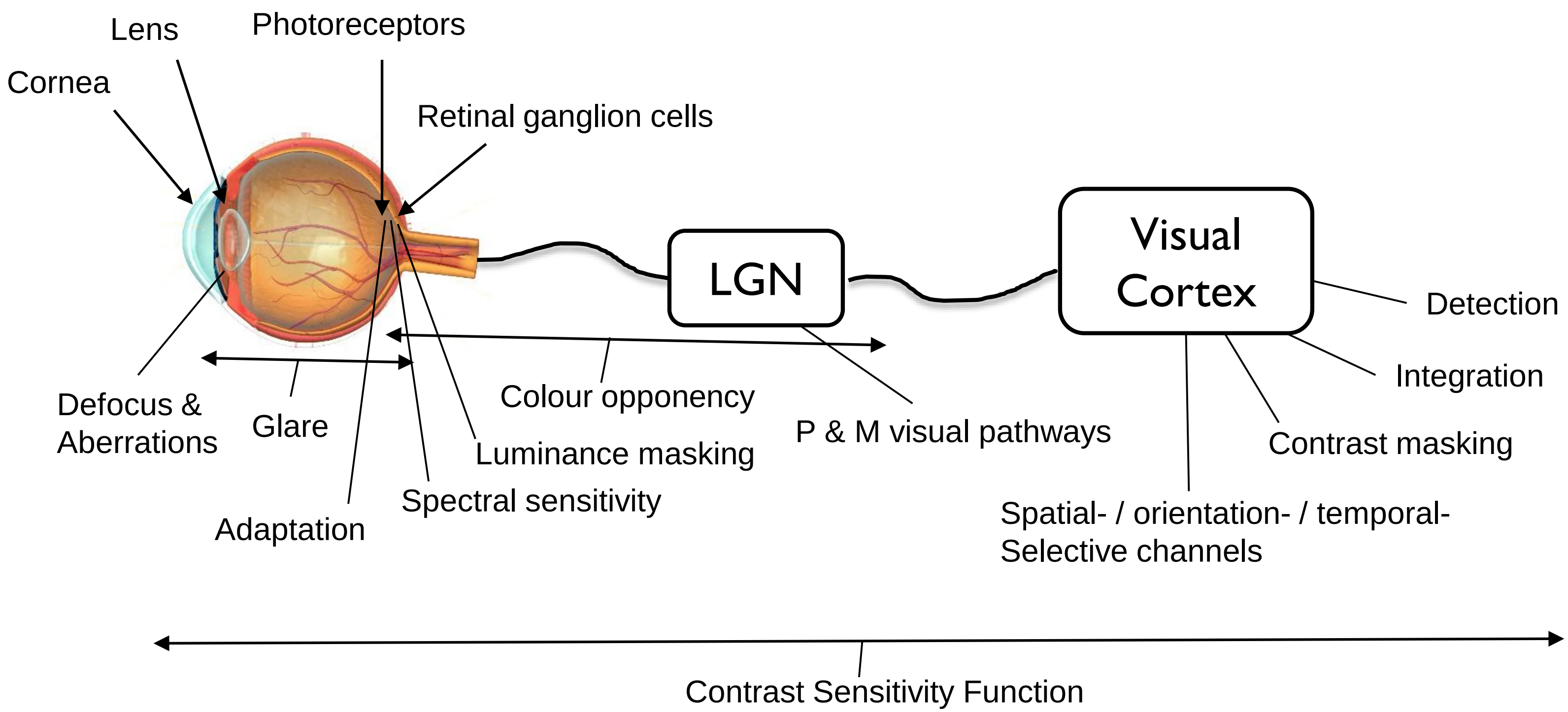
$$Y = gX + \eta$$

Convolution kernel

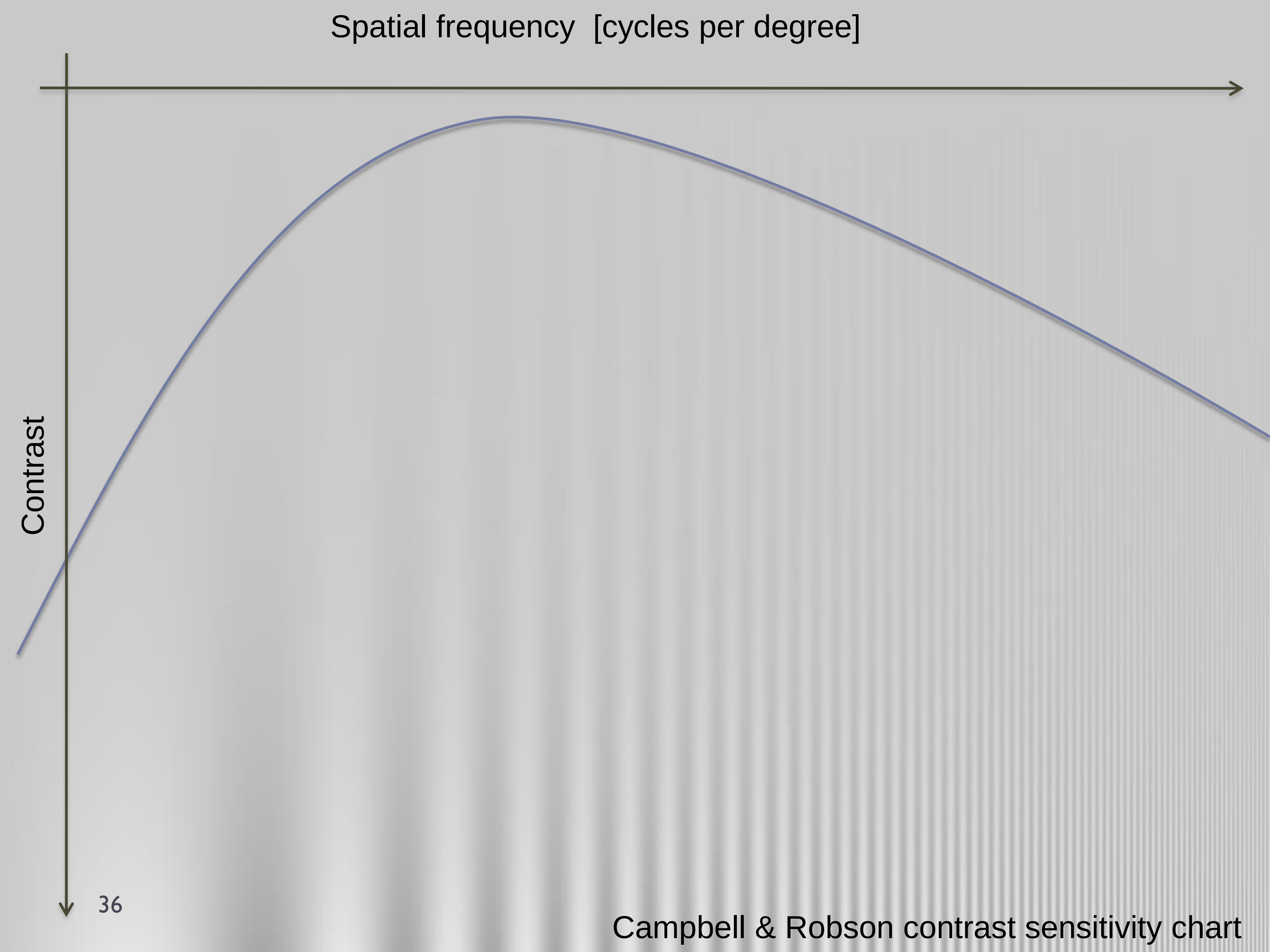
Noise

- Can we come up with a similar model for visual system?

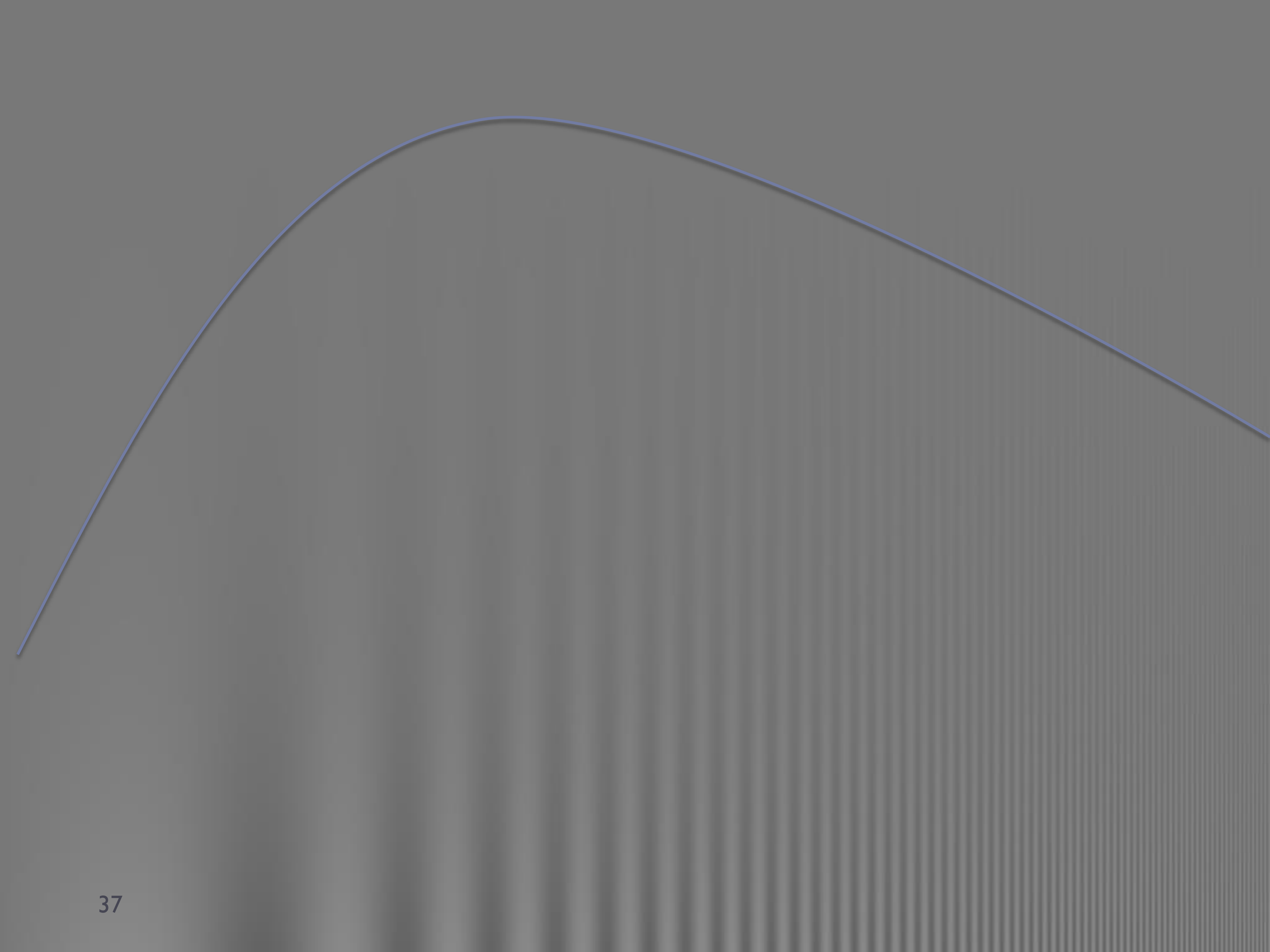
Modeling visual system



Excellent visualization of the human eye:
https://animagraffs.com/human-eye/



Campbell & Robson contrast sensitivity chart



Contrast Sensitivity Function

Temporal frequency

Stimulus size

Spatial frequency

Eccentricity

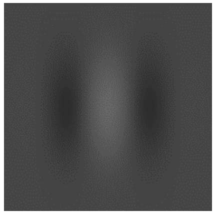
$$CSF = S(r, q, w, l, i^2, d, e)$$

Orientation

Viewing distance

Adapting luminance

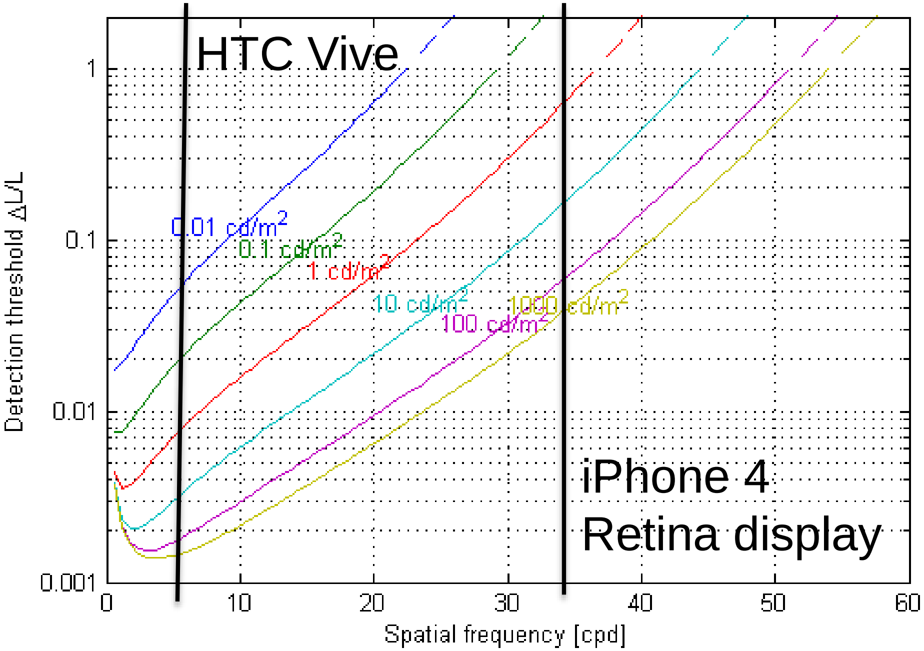
Contrast Sensitivity Function



- Sensitivity = inverse of the detection threshold

$$S = \frac{L_b}{\Delta L}$$

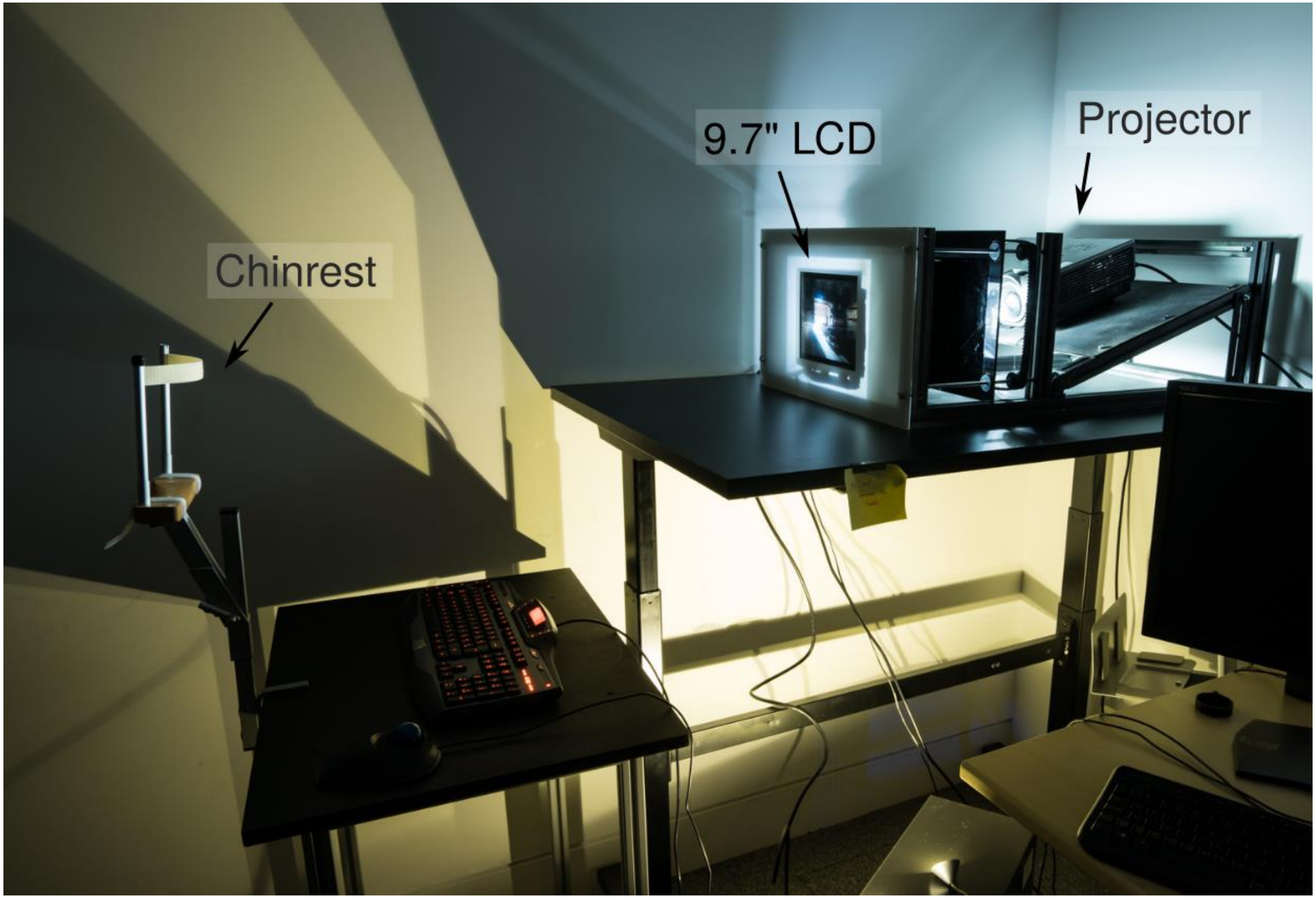
- Detection of barely noticeable luminance difference ΔL on a uniform background L_b
- Varies with luminance



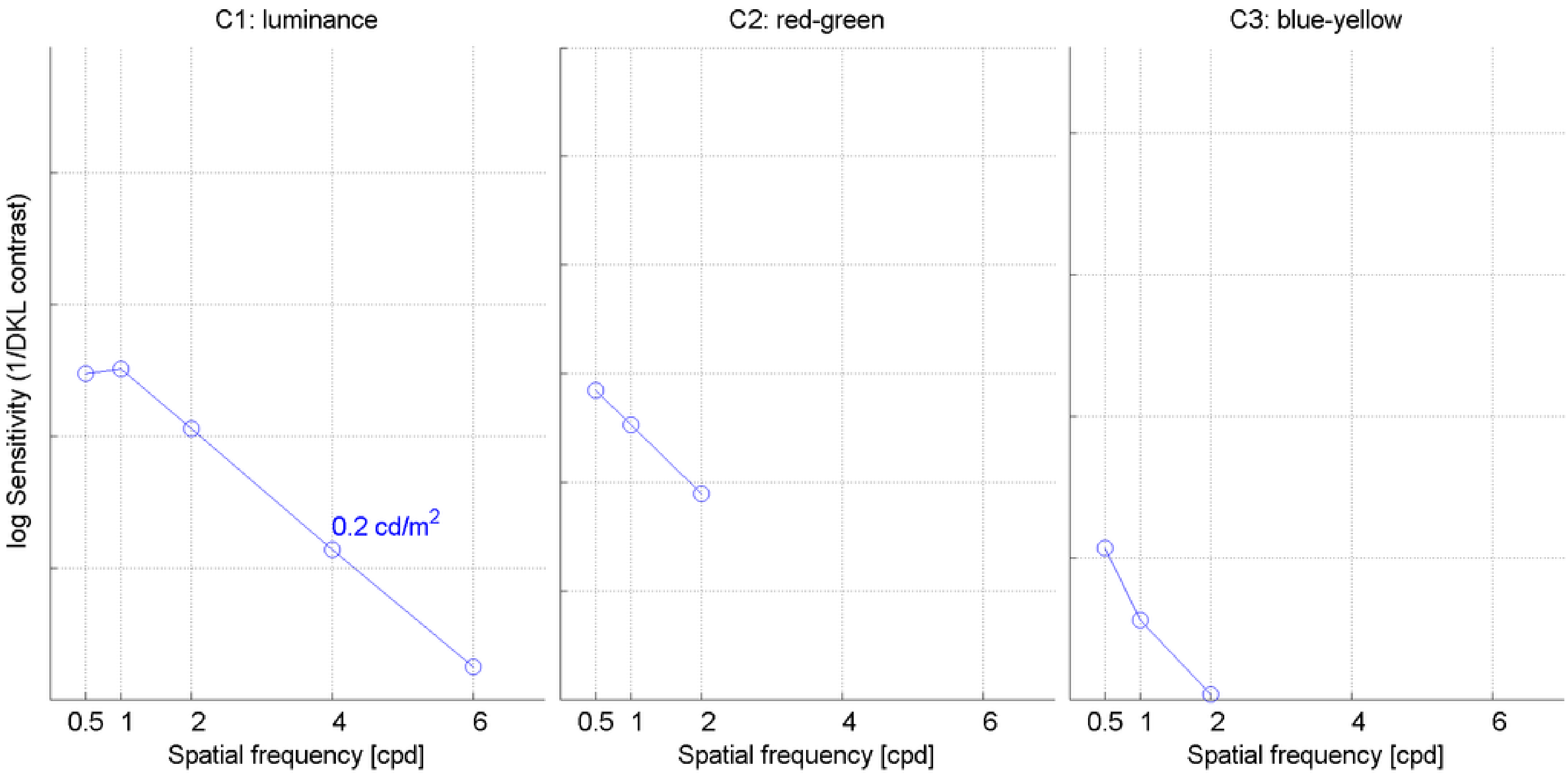
CSF models:
Barten, P. G. J. (2004). https://doi.org/10.1117/12.537476
Mantiuk, R., Kim, K. J., Rempel, A. G., & Heidrich, W. (2011) https://doi.org/10.1145/2010324.1964935

Spatio-chromatic CSF

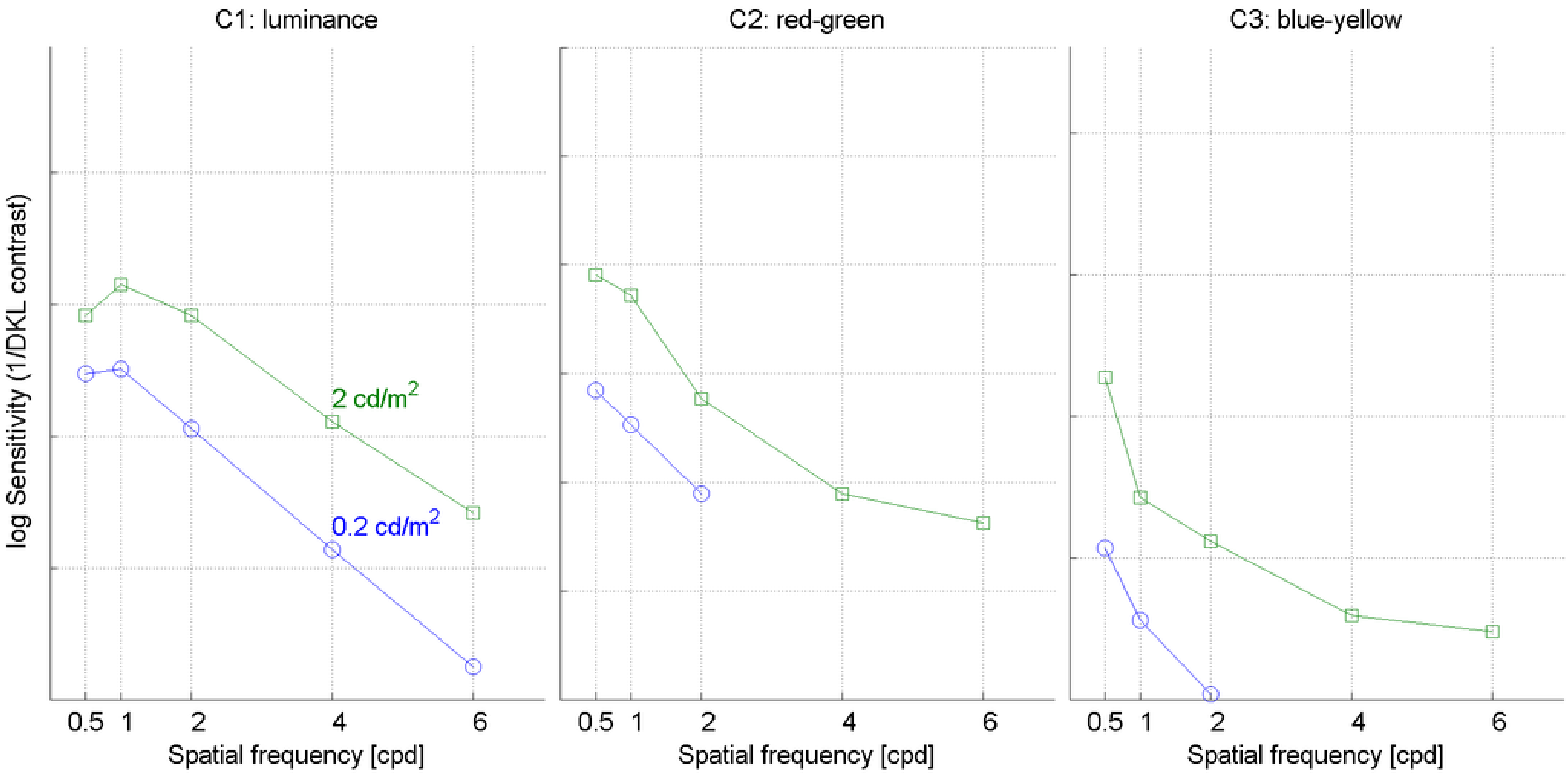
High brightness HDR display [15,000 cd/m^2]



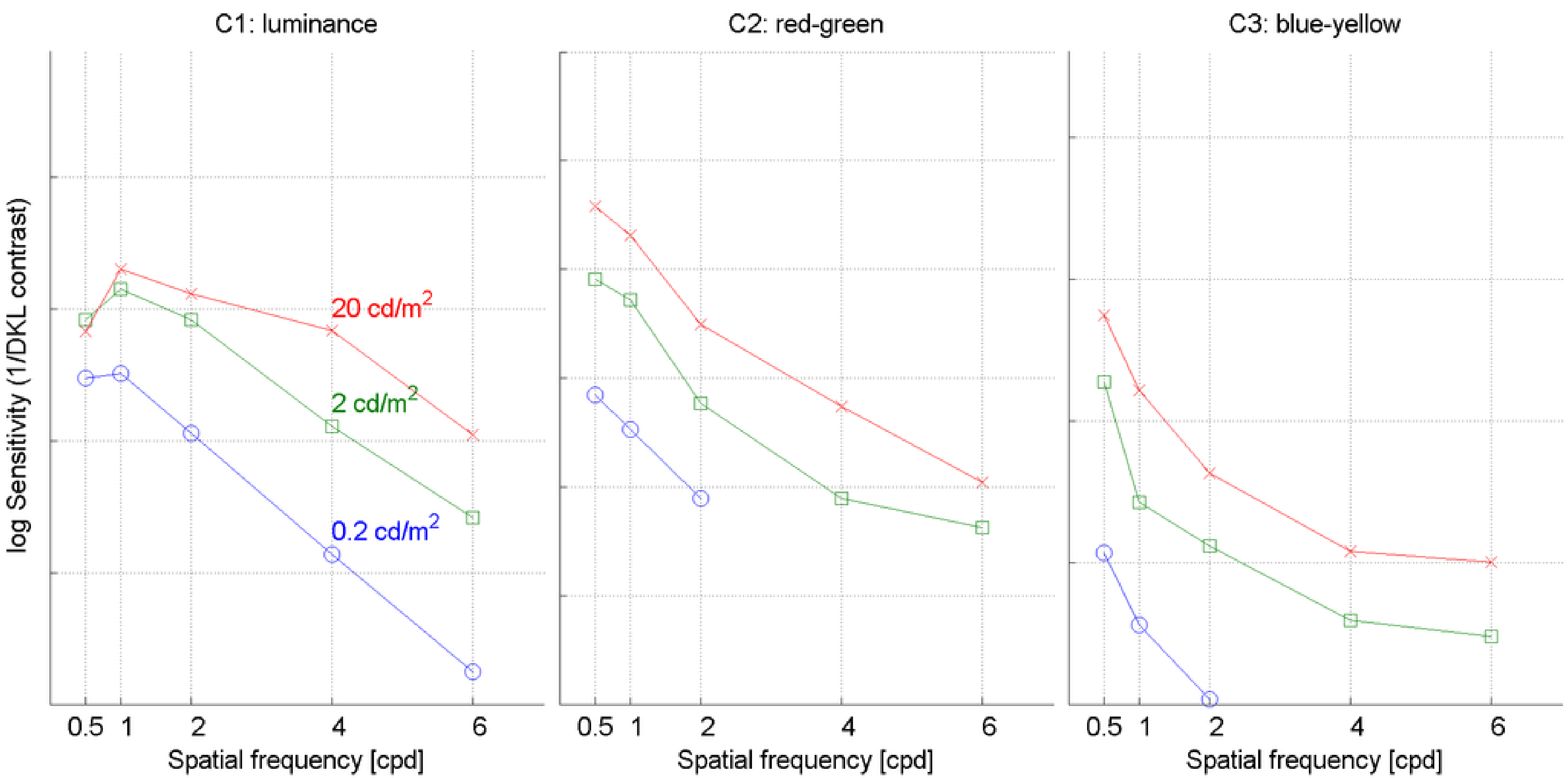
Color CSF across the luminance range



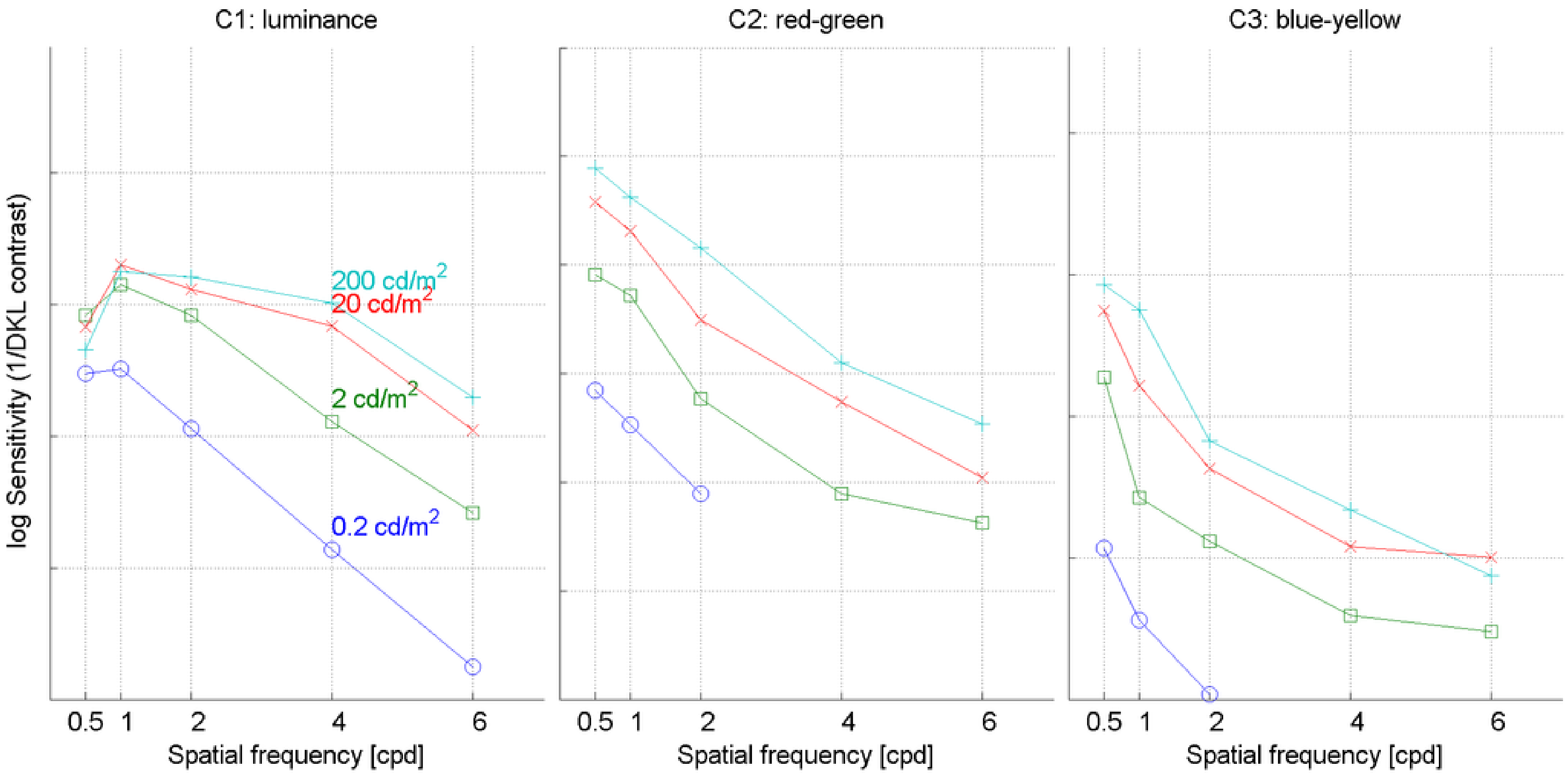
Color CSF across the luminance range



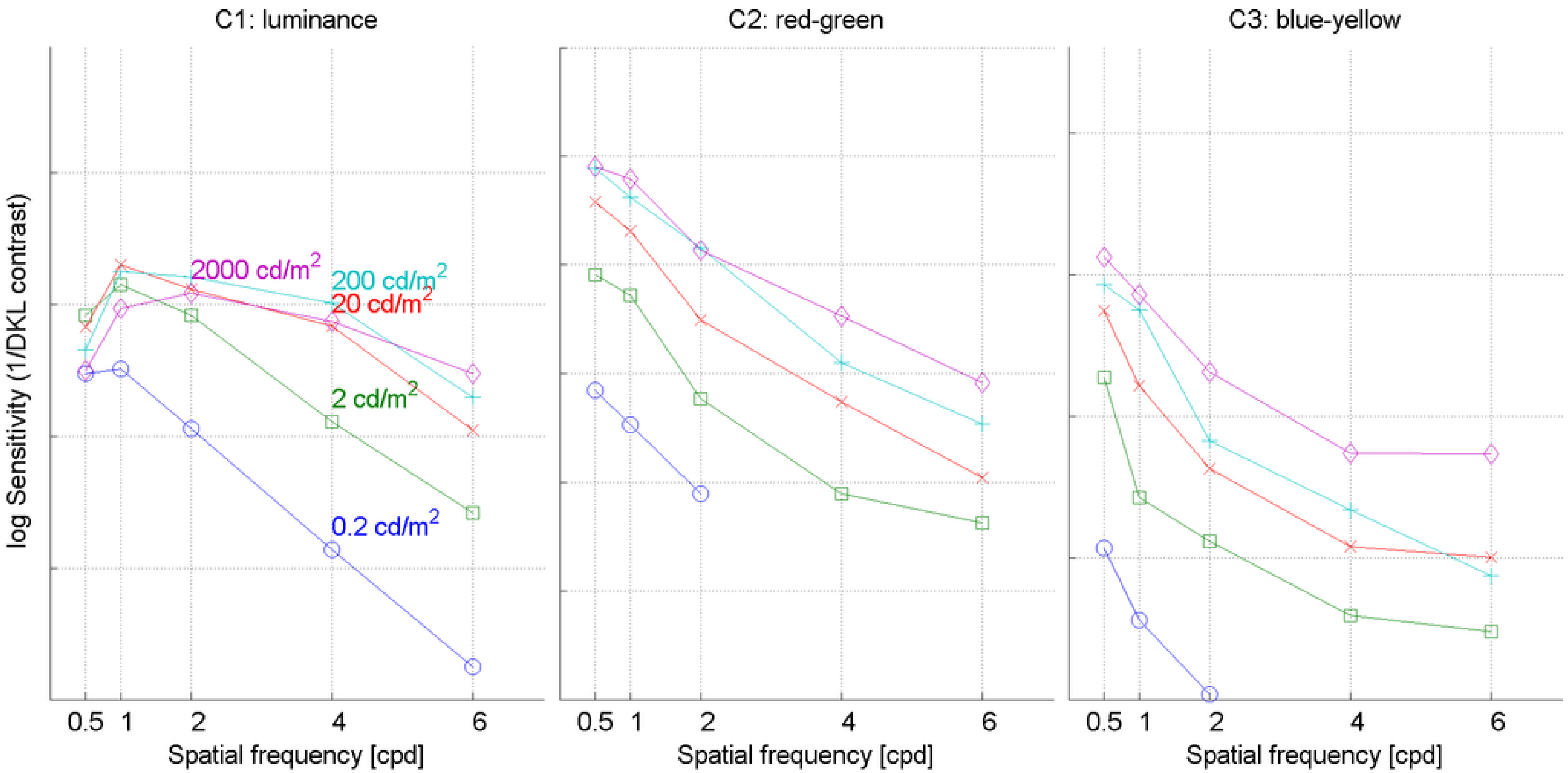
Color CSF across the luminance range



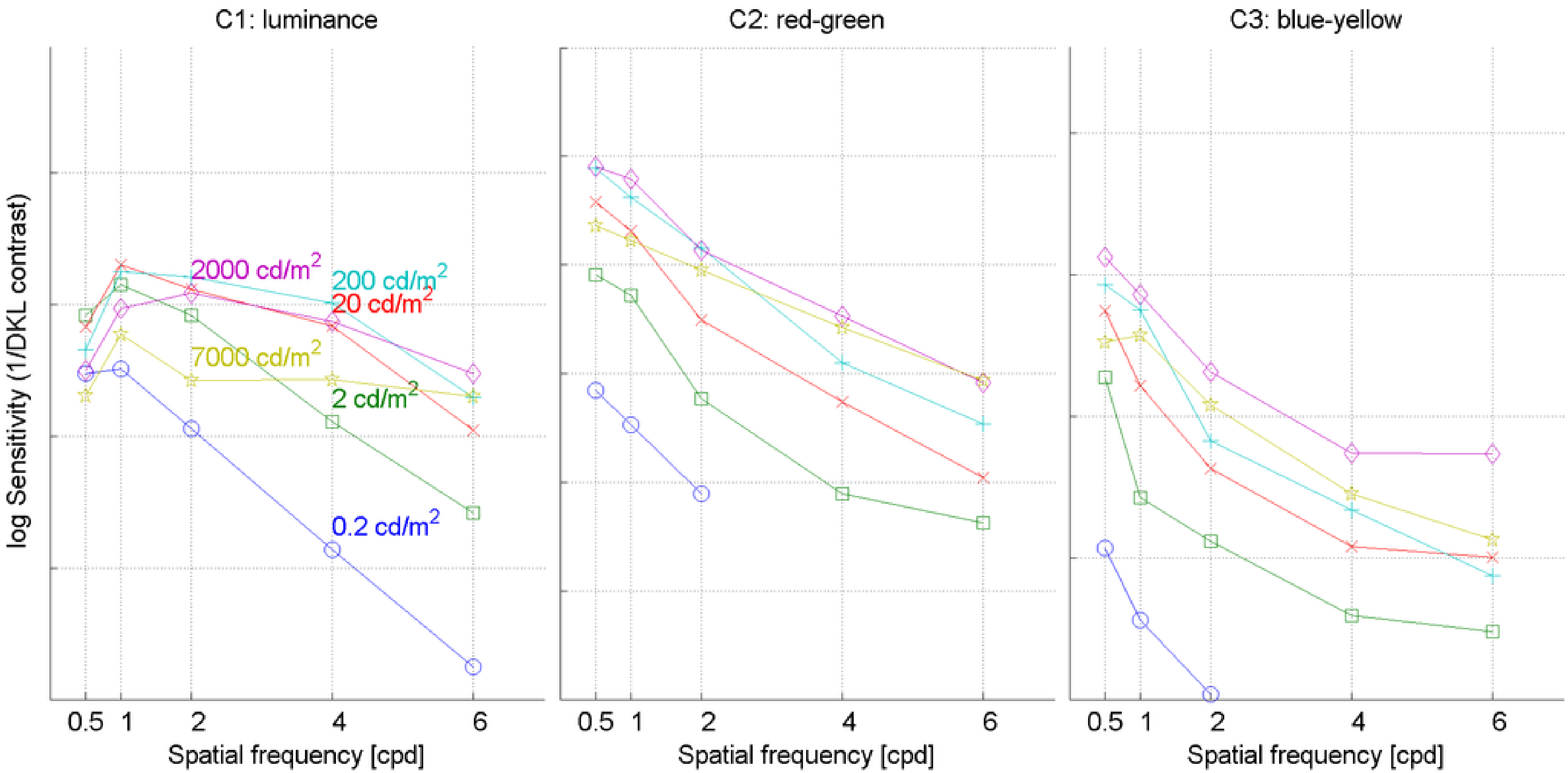
Color CSF across the luminance range



Color CSF across the luminance range



Color CSF across the luminance range



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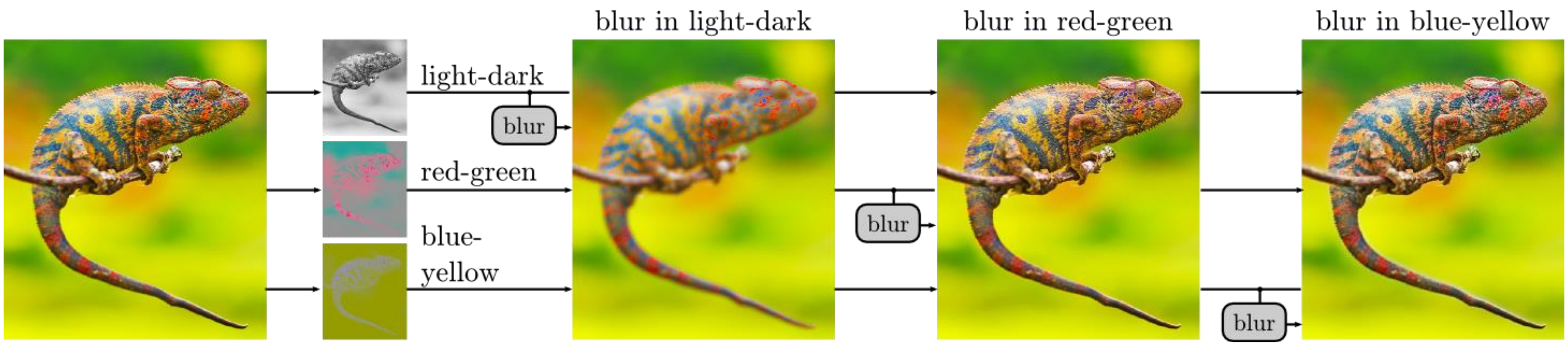
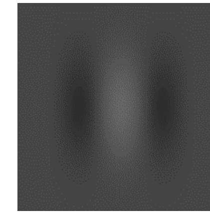
Spatio-chromatic CSF

- Chromatic channels (red-green, blue-yellow) are much less sensitive to high frequencies

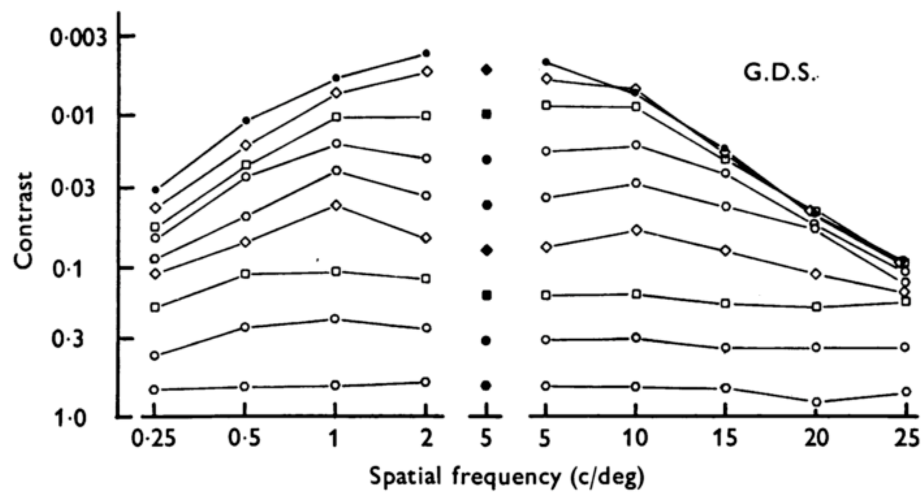


- This is why we can (often) get away with chroma subsampling in image/video compression

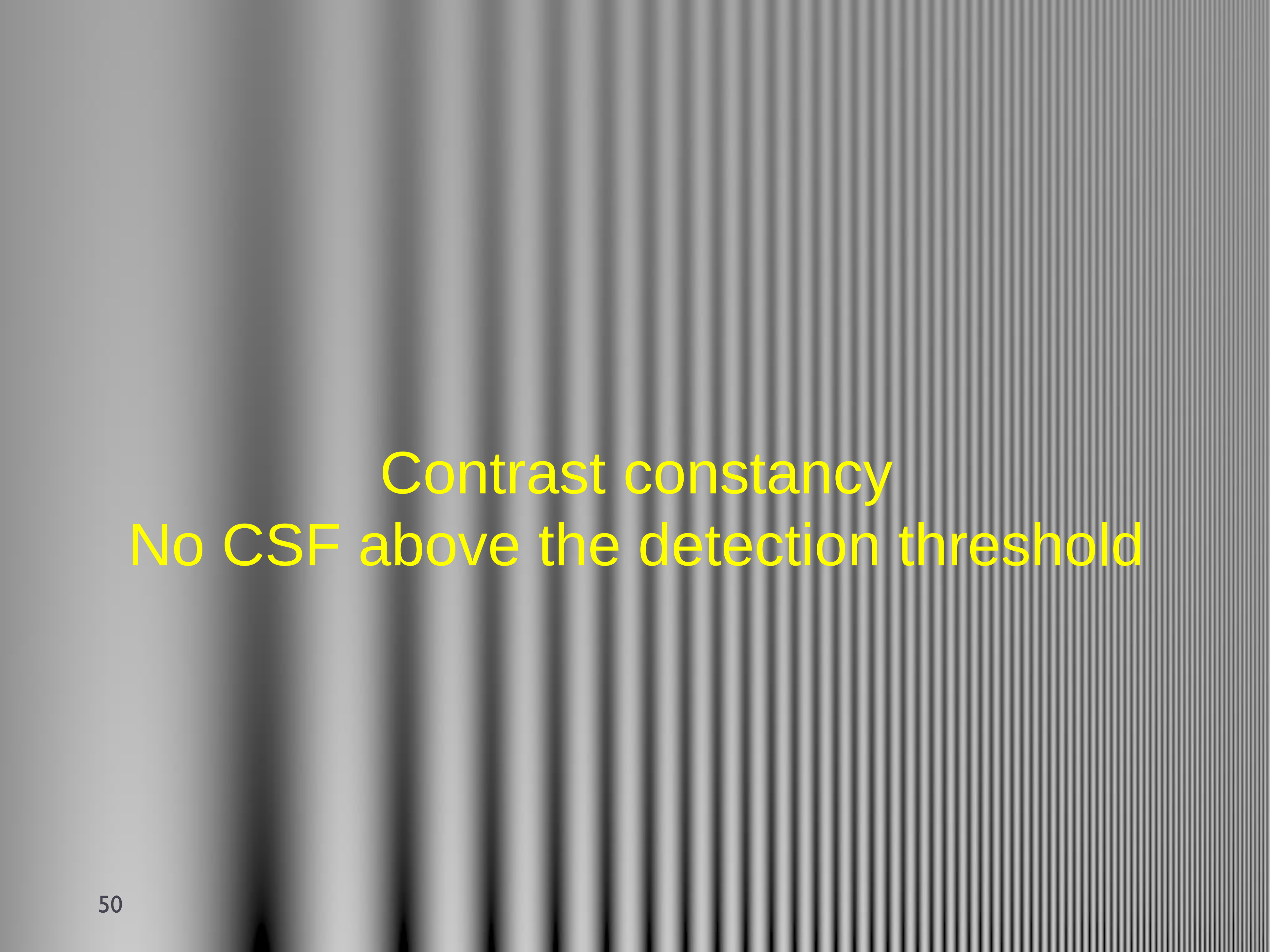
Contrast Constancy



- CSF is NOT MTF of visual system
  - Contrast constancy
  - There is little variation in magnitude of perceived contrast above the detection threshold



Georgeson and Sullivan. 1975. J. Phsysio


Contrast constancy
No CSF above the detection threshold

Modeling visual perception

- Since visual system is highly non-linear, a linear model

$$Y = gX + \eta$$

CSF is NOT MTF!

cannot be used.

- Visual processing is an unknown non-linear function:

Input image

Percept (not an image)

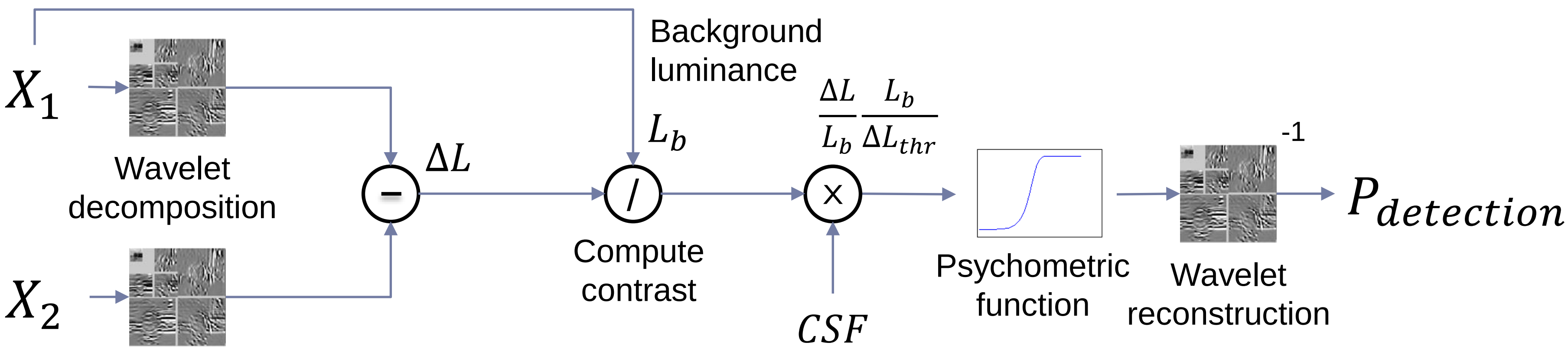
$$Y = f[X]$$

Visual processing

Predicting visible differences with CSF

- But we can use CSF to find the probability of spotting a difference beween a pair of images X_1 and X_2:

$$p(f[X_1] = f[X_2]\,|X_1, X_2, CSF)$$



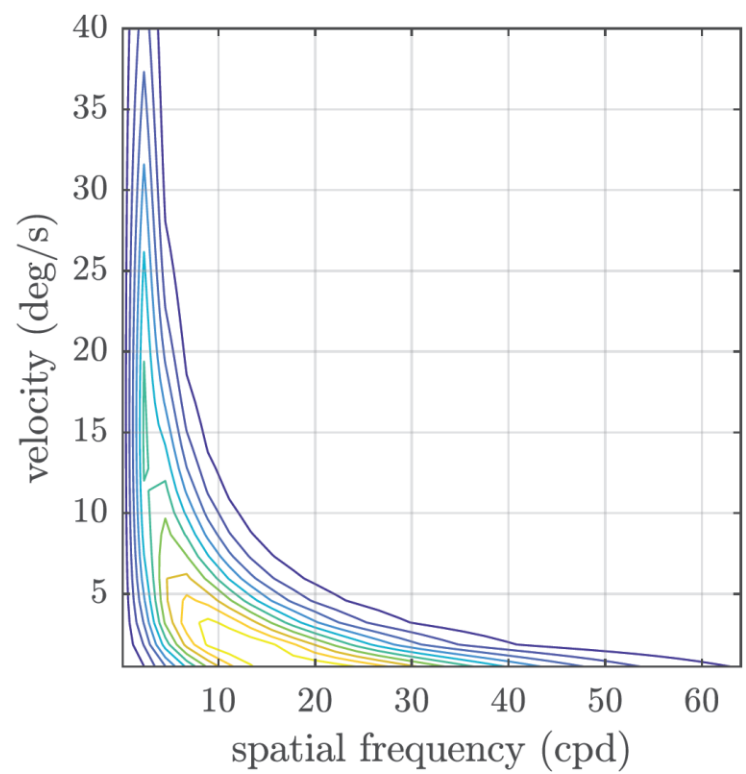
(simplified) Visual Difference Predictor

Daly, S. (1993).
Mantiuk, R., et al. (2011)
https://doi.org/10.1145/2010324.1964935

Retinal velocity

- Sensitivity drops rapidly once images start to move
- The eye tracks moving objects
  - Smooth Pursuit Eye Motion (SPEM)
  - Stabilizes images on the retina
  - But tracking is not perfect
- Loss of sensitivity mostly caused by imperfect SPEM
  - SPEM worse at high velocities
- Motion sharpenning
  - Masks the loss of higher frequencies

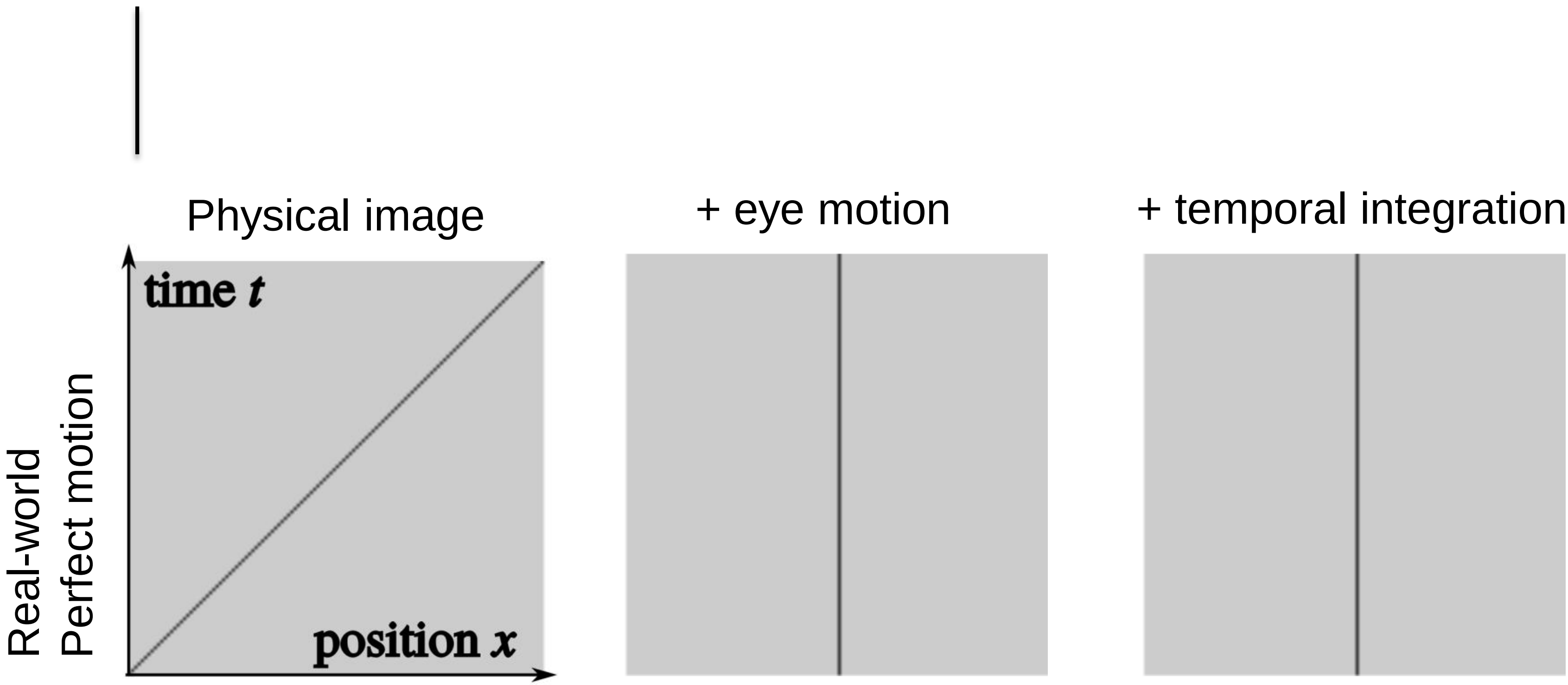
Spatio-velocity contrast sensitivity



Kelly's model [1979]

Hold-on blur

- The eye smoothly follows a moving object
- But the image on the display is "frozen" for 1/60th of a second



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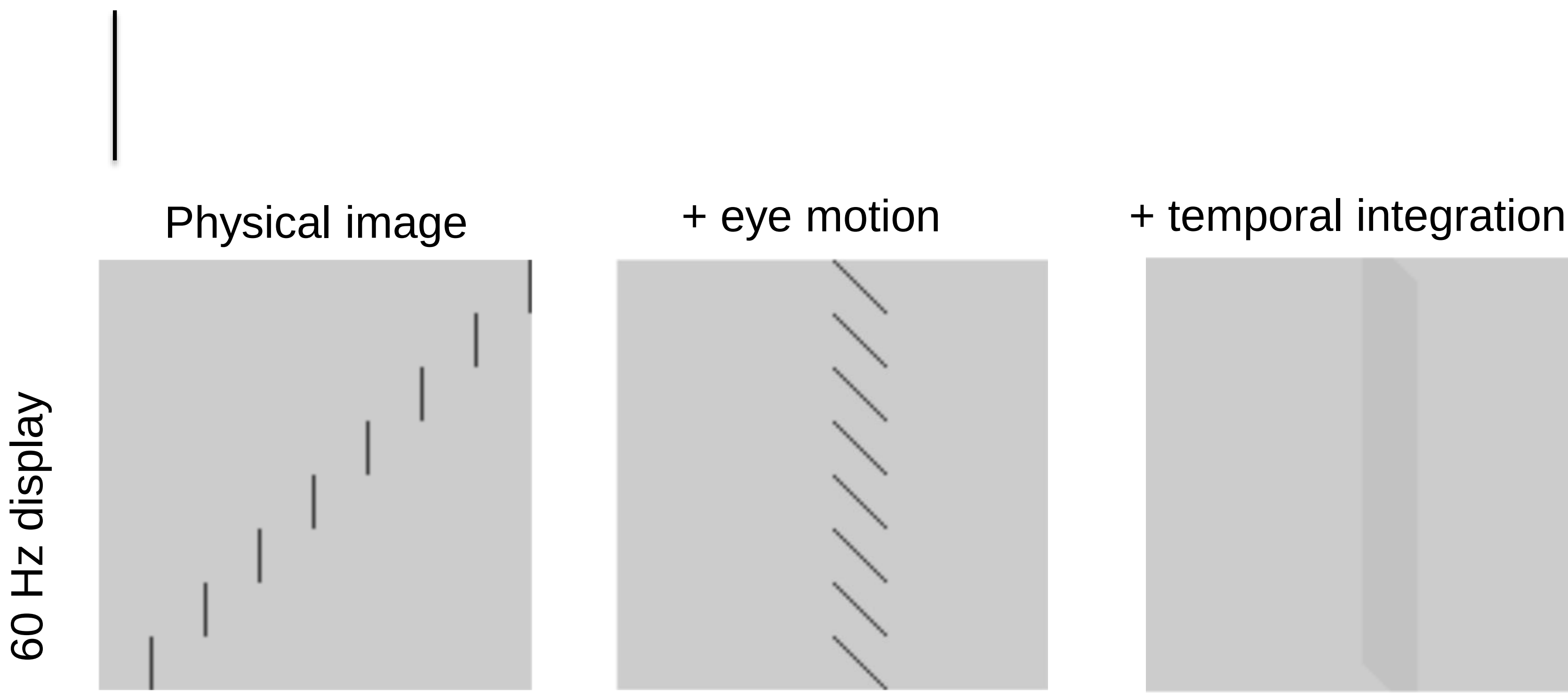

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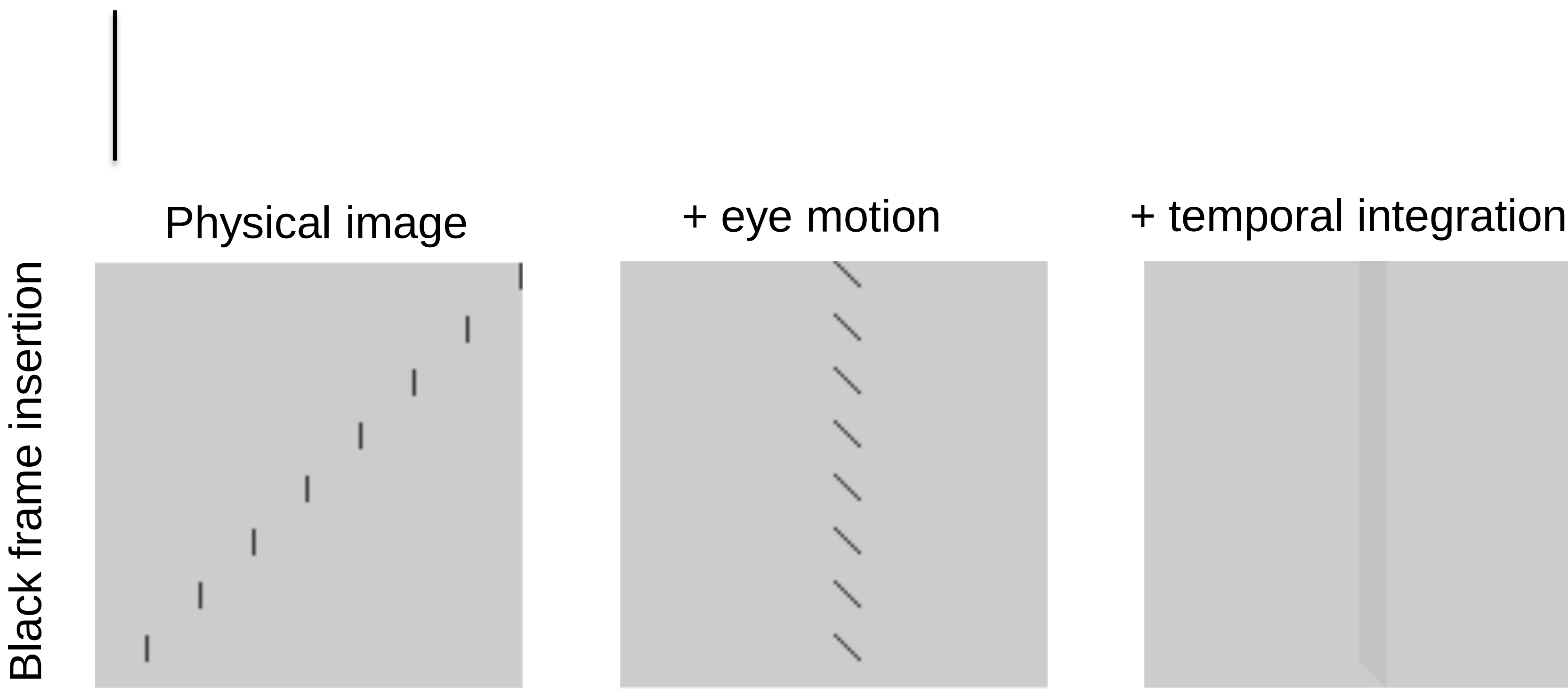

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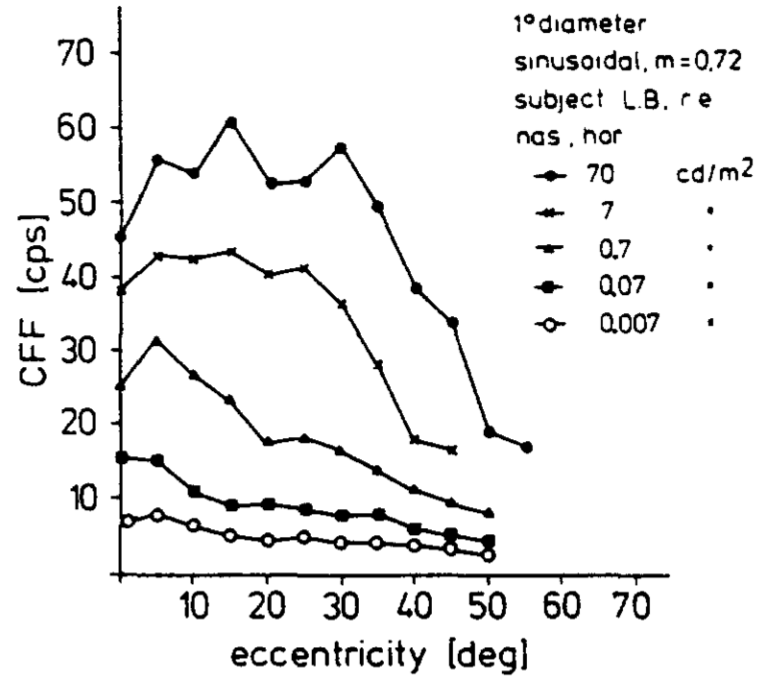
Flicker

- Critical Flicker Frequency
  - Strongly depends on luminance – big issue for HDR VR headsets
  - Increases with eccentricity
  - and stimulus size
  - It is possible to detect flicker even at 2kHz
    - For saccadic eye motion



[Hartmann et al. 1979]

Simulation (cyber) sickness

- Conflict between vestibular and visual systems
  - When camera motion inconsistent with head motion
  - Frame of reference (e.g. cockpit) helps
  - Worse with larger FOV
  - Worse with high luminance and flicker

ToC

VR rendering – required bandwidth

$$2 \times (1400 \times 1600) \times 90 \times 3 \approx 1.13\text{GBps} \approx 9\text{Gbps}$$

2 eyes

resolution

refresh rate

pixel data

TRM: Temporal Resolution Multiplexing

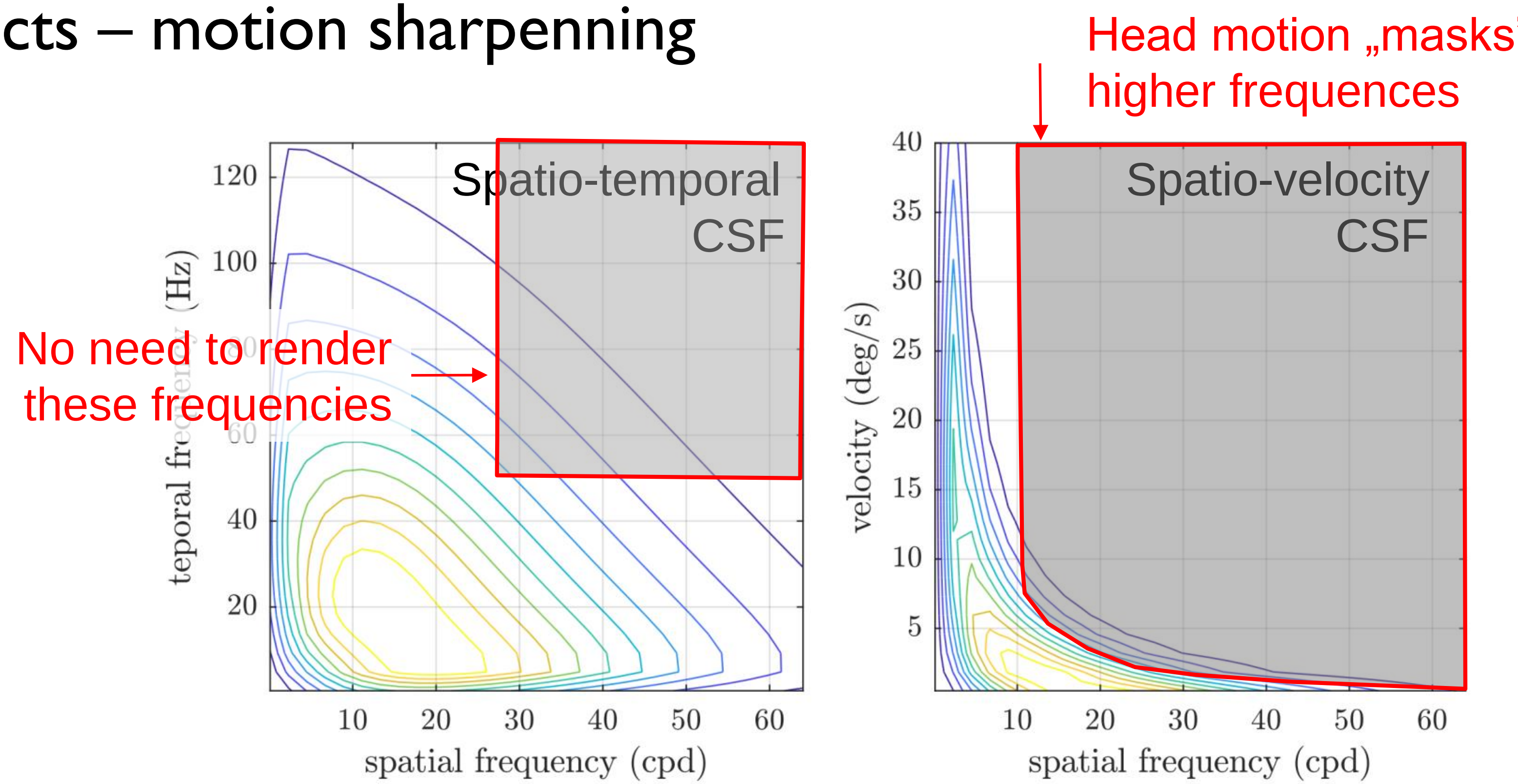
- Render every second frame at a lower resolution
- Transfer high- and low-resolution frames
- When displaying
  - Compensate for the loss of high frequencies
  - Model display and its limitations
  - Handle the limited dynamic range

See the demo in the break!

[Denes et al. 2019, Temporal Resolution Multiplexing …, TCVCG/IEEE VR]

TRM: Why does it work?

- The eye cannot see high spatio-temporal frequencies
- The eye cannot see the loss of sharpness for moving objects – motion sharpenning



Summary

- VR/AR display technologies must exploit the limitations of the visual system
  - Because the display / rendering bandwidth is becoming too large
- HDR for VR is a great idea because
  - It gives more realistic experience
  - Better quality with the same number of pixels
  - Additional depth cues
- HDR for VR is bad idea because
  - Increased flicker visibility
  - Increased simulation sickness
  - Lens glare will reduce the effective dynamic range

References

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