Models of early visual perception

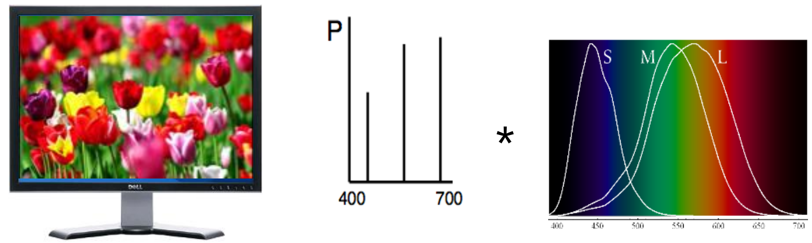
Advanced Graphics and Image Processing

Rafal Mantiuk

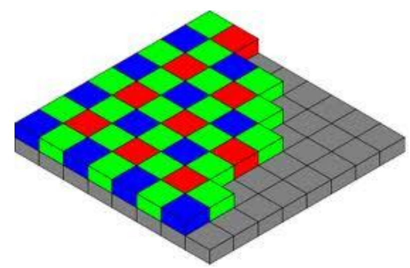
Computer Laboratory, University of Cambridge

Many graphics/display solutions are motivated by visual perception

Image & video compression

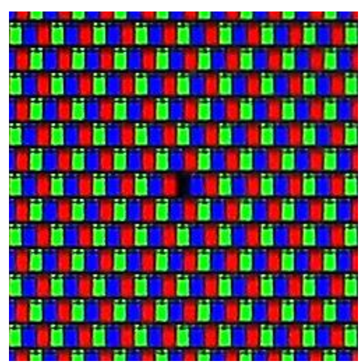


Display spectral emission - metamerism

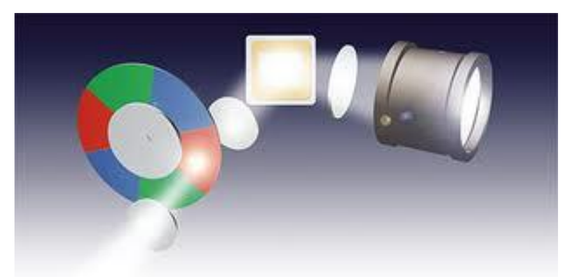


Camera's Bayer pattern

Halftonning



Display's subpixels



Color wheel in DLPs

…

Perceived brightness of light

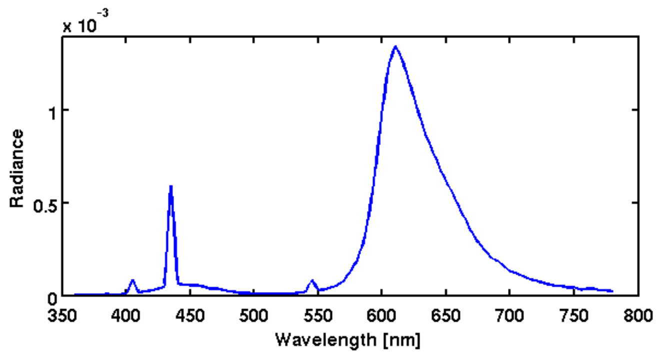
Luminance (again)

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

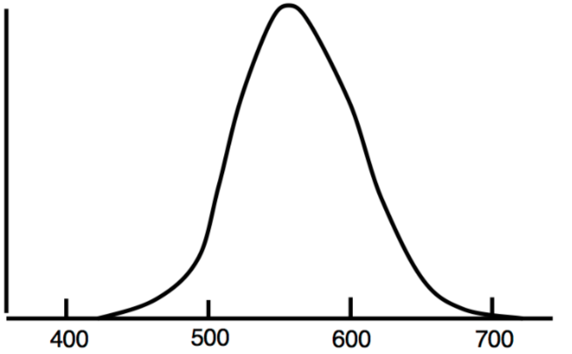
Luminance

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

Light spectrum (radiance)



Luminous efficiency function (weighting)



Steven’s power law for brightness

- Stevens (1906-1973) measured the perceived magnitude of physical stimuli
  - Loudness of sound, tastes, smell, warmth, electric shock and brightness
  - Using the magnitude estimation methods
    - Ask to rate loudness on a scale with a known reference
- All measured stimuli followed the power law:

$$j\,(I) = kI^{a}$$

Perceived magnitude

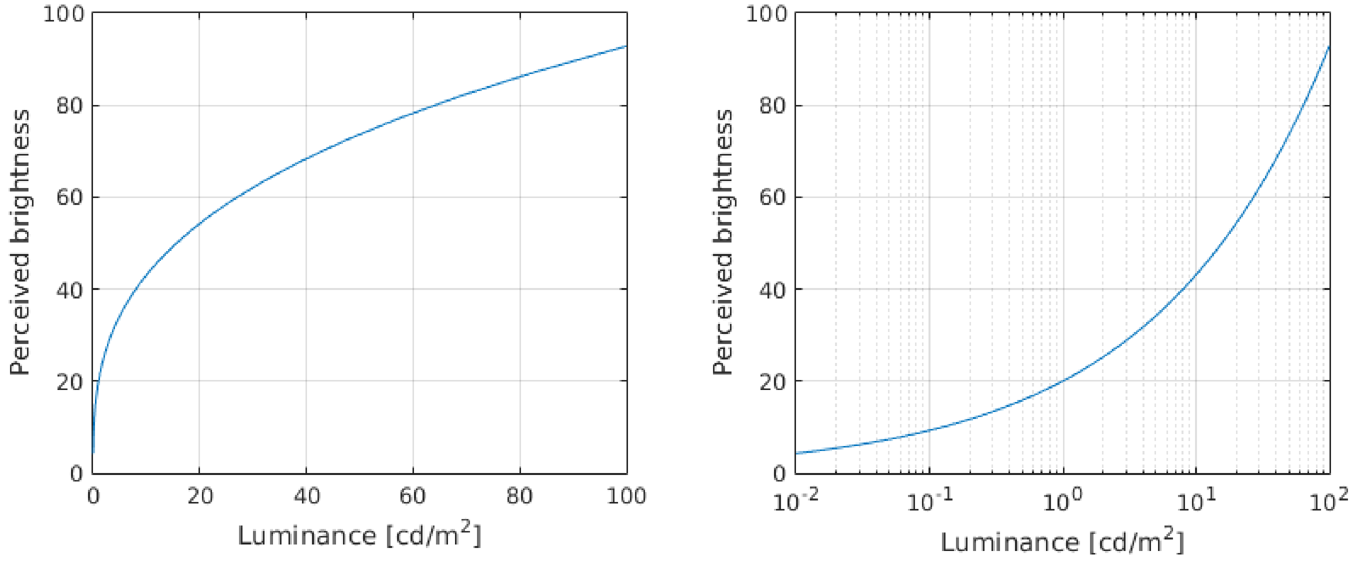
Exponent

Constant

Physical stimulus

- For brightness (5 deg target in dark), a = 0.3

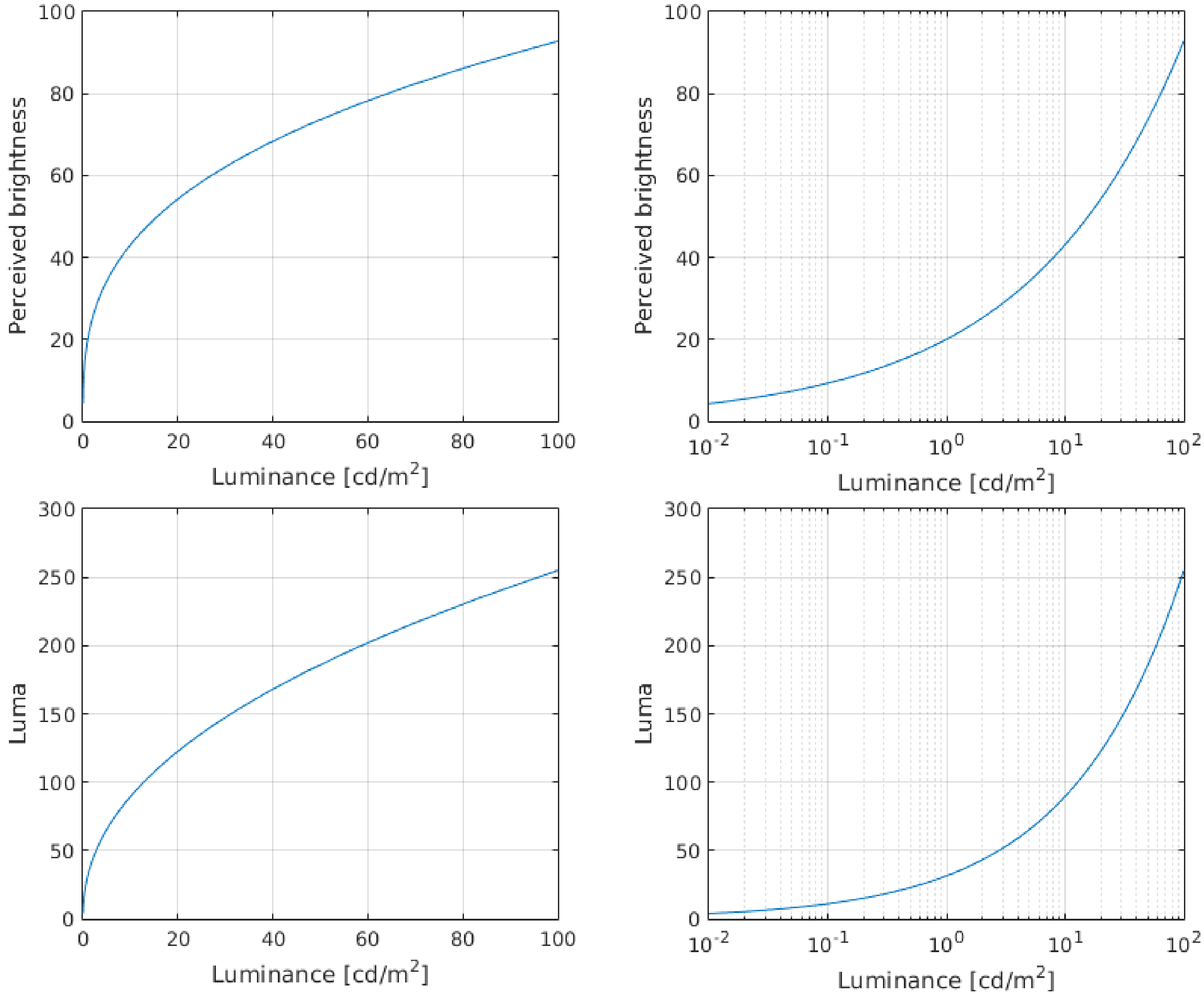
Steven's law for brightness



Steven’s law vs. Gamma correction

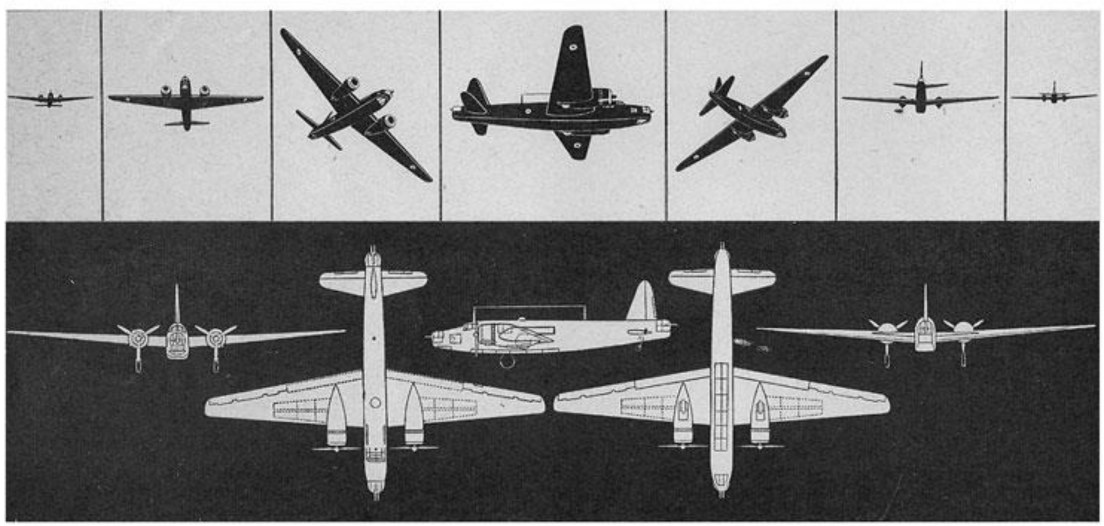
Stevens’ law
a=0.3

Gamma function
Gamma = 2.2



Detection and discrimination

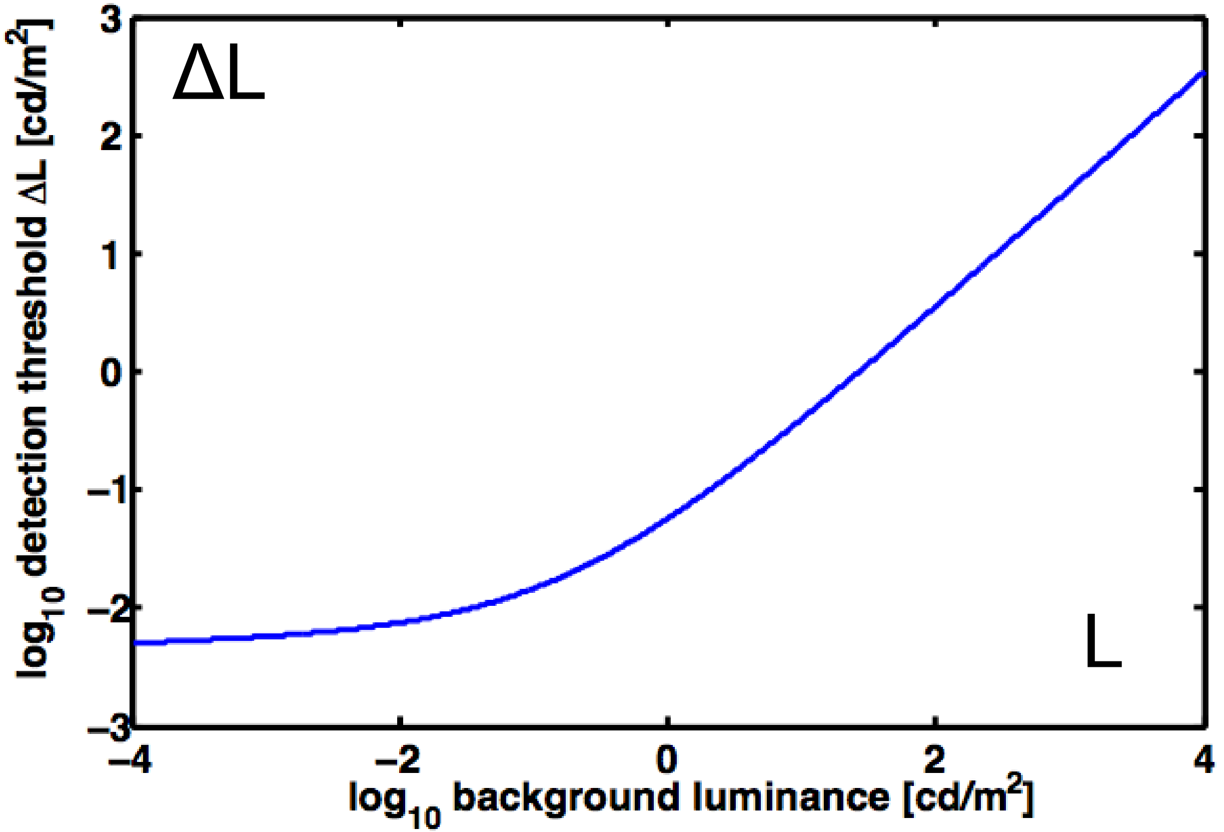
Detection thresholds

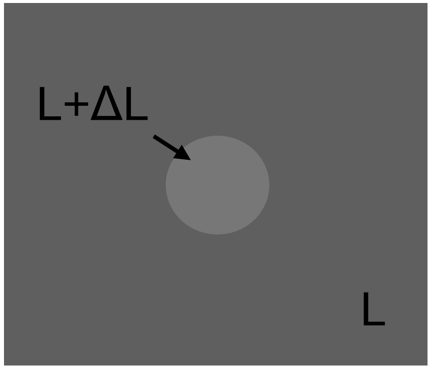


- The smallest detectable difference between
  - the luminance of the object and
  - the luminance of the background

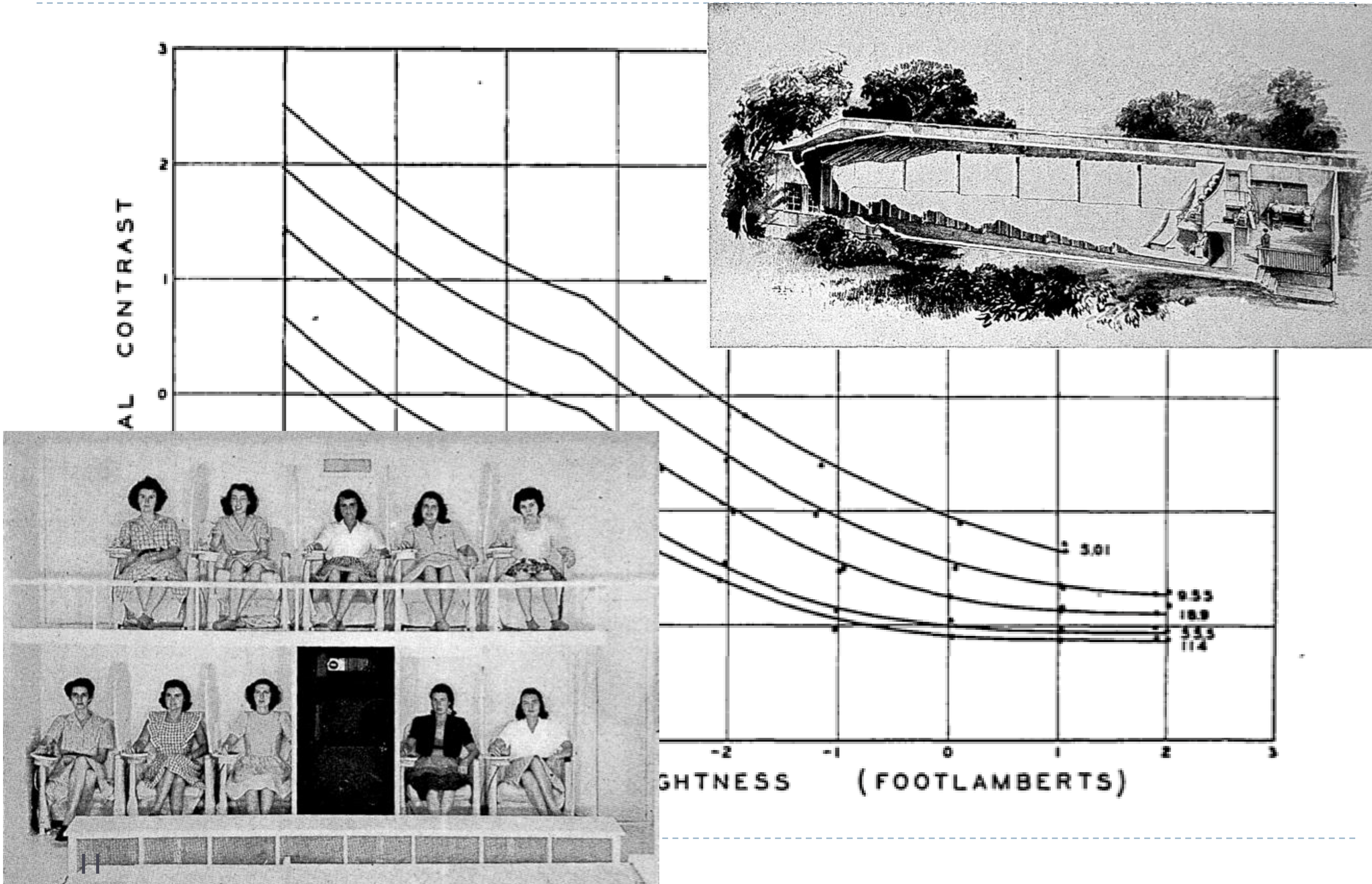
Threshold versus intensity (t.v.i.) function

- The smallest detectable difference in luminance for a given background luminance

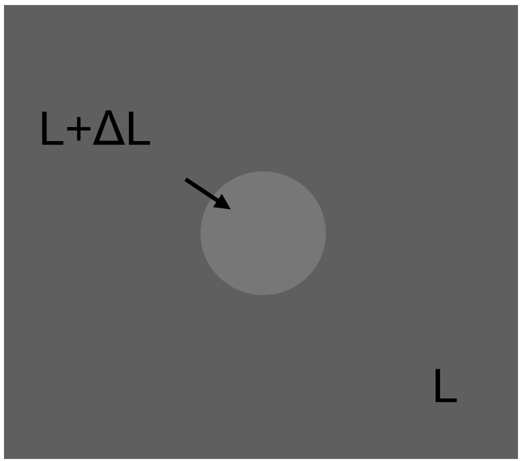


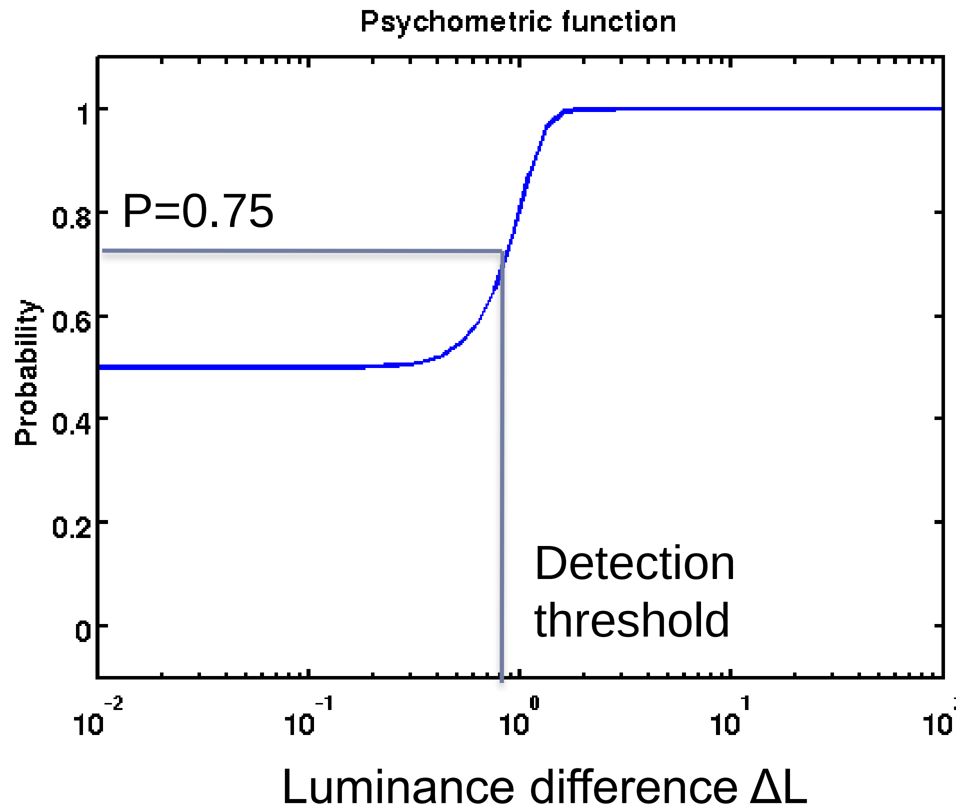


t.v.i. measurements – Blackwell 1946



Psychophysics
Threshold experiments

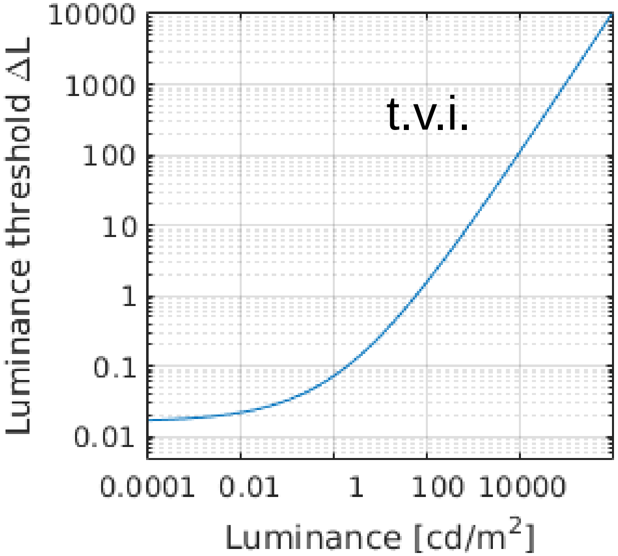




t.v.i function / c.v.i. function / Sensitivity

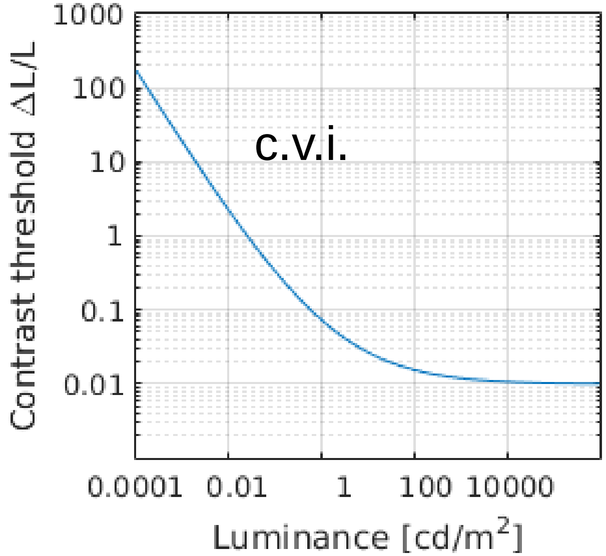
- The same data, different representation

Threshold vs. intensity



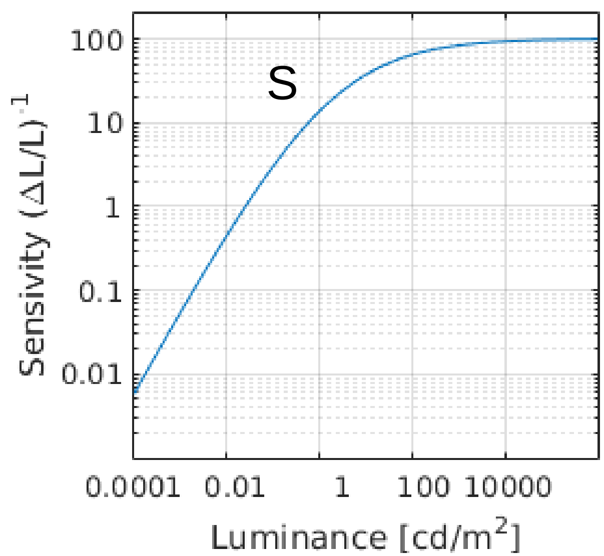
$$\Delta L = L_{disk} - L_{background}$$

Contrast vs. intensity



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

Sensitivity



$$S = \frac{1}{T} = \frac{L}{\Delta L}$$

Sensitivity to luminance

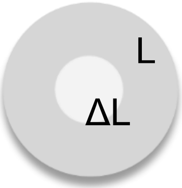
- Weber-law – the just-noticeable difference is proportional to the magnitude of a stimulus

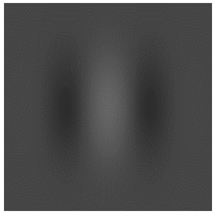
Ernst Heinrich Weber
[From wikipedia]

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

- ΔL: The smallest detectable luminance difference
- L: Background (adapting) luminance
- k: Constant

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!

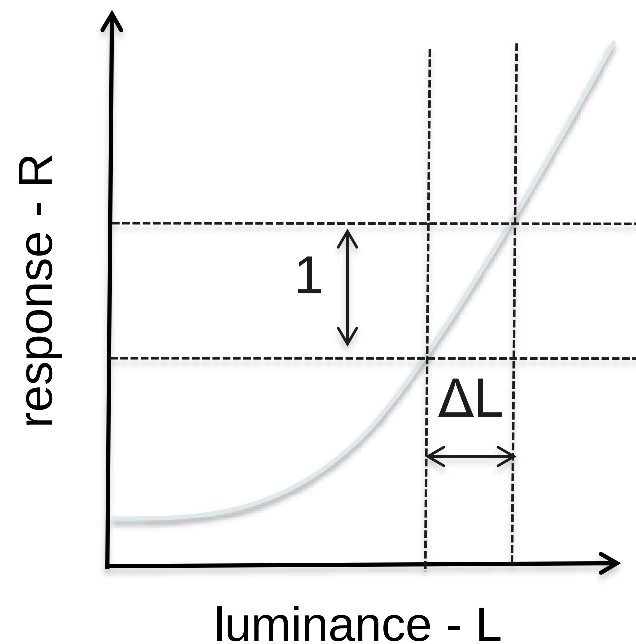
How to make luminance (more) perceptually uniform?

- Using "Fechnerian" integration

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

Derivative of response

Detection threshold



Luminance transducer: $$R(L) = \int_{L_{min}}^{L} \frac{1}{\Delta L(l)} dl$$

Assuming the Weber law

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

- and given the luminance transducer

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

- 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

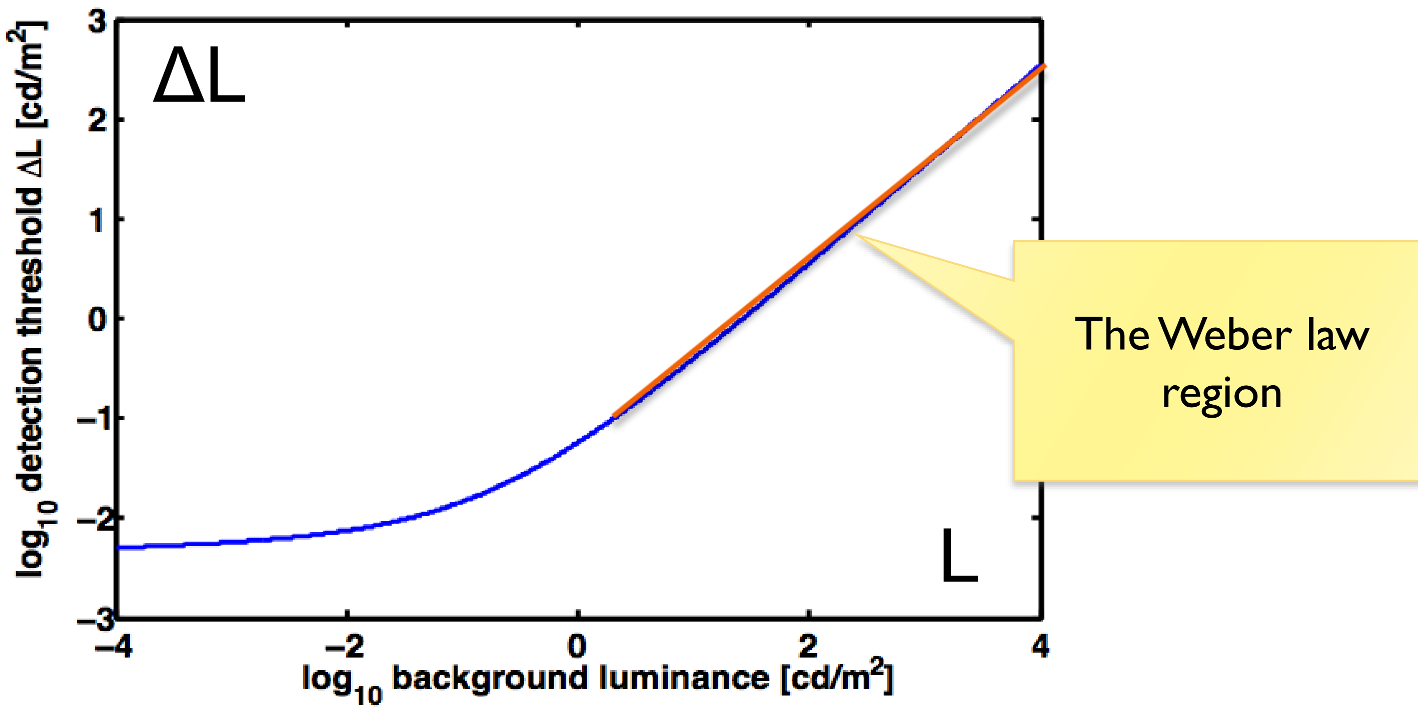
$$R(L) = a \ln(L)$$

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

Gustav Fechner
[From Wikipedia]

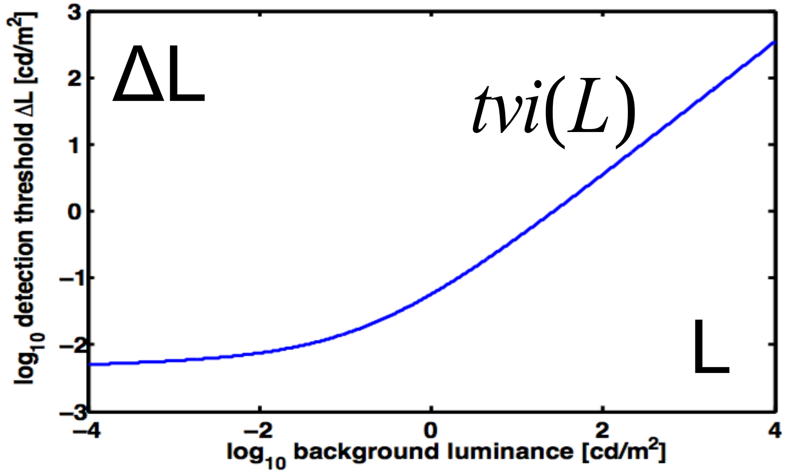
But…the Fechner law does not hold for the full luminance range

- Because the Weber law does not hold either
- Threshold vs. intensity function:



Weber-law revisited

- If we allow detection threshold to vary with luminance according to the t.v.i. function:

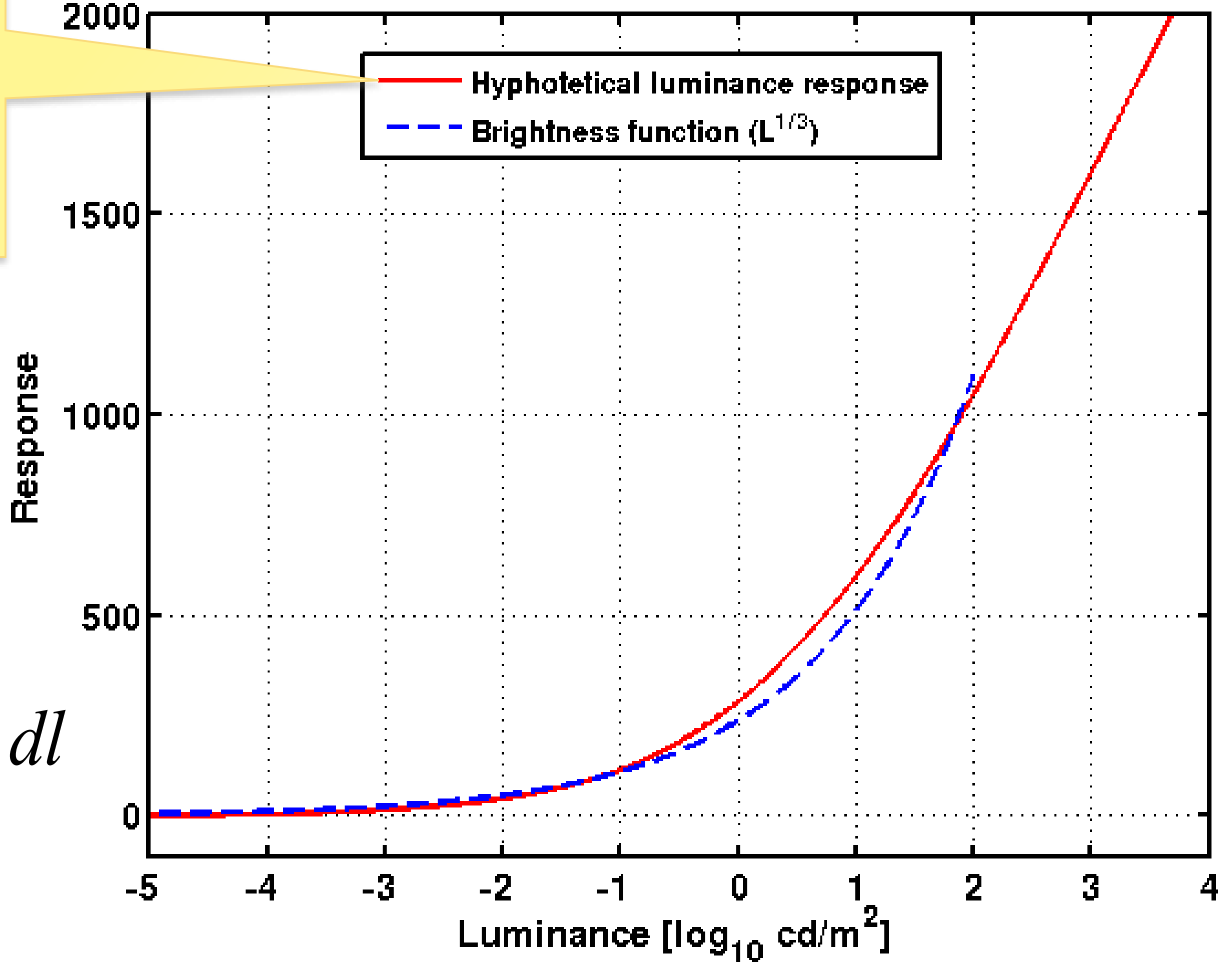


- we can get a more accurate estimate of the "response":

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

Fechnerian integration and Stevens' law

R(L) - function derived from the t.v.i. function

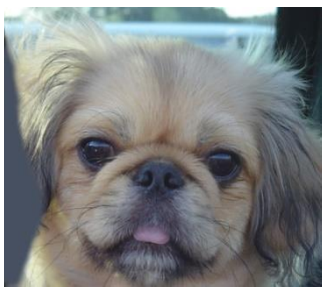


$$R(L) = \int_0^L \frac{1}{tvi(l)} dl$$

Applications of JND encoding – R(L)

- DICOM grayscale function
  - Function used to encode signal for medial monitors
  - 10-bit JND-scaled (just noticeable difference)
  - Equal visibility of gray levels
- HDMI 2.0a (HDR10)
  - PQ (Perceptual Quantizer) encoding
  - Dolby Vision
  - To encode pixels for high dynamic range images and video

DOLBY
VISION
The Future of Vision

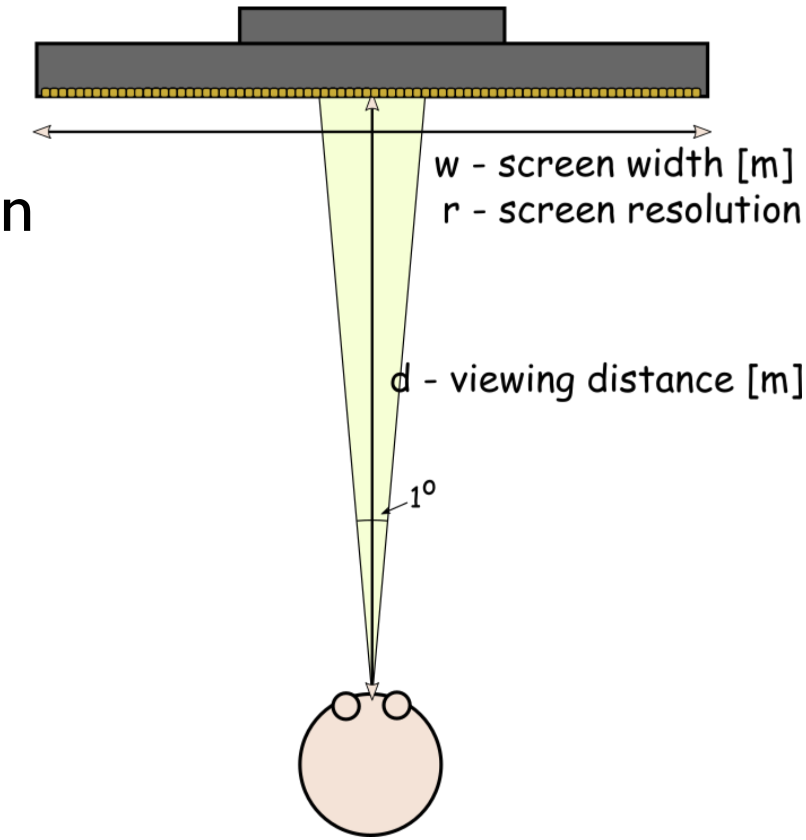



© 2006 Aude Oliva & Antonio Torralba

Spatial contrast sensitivity

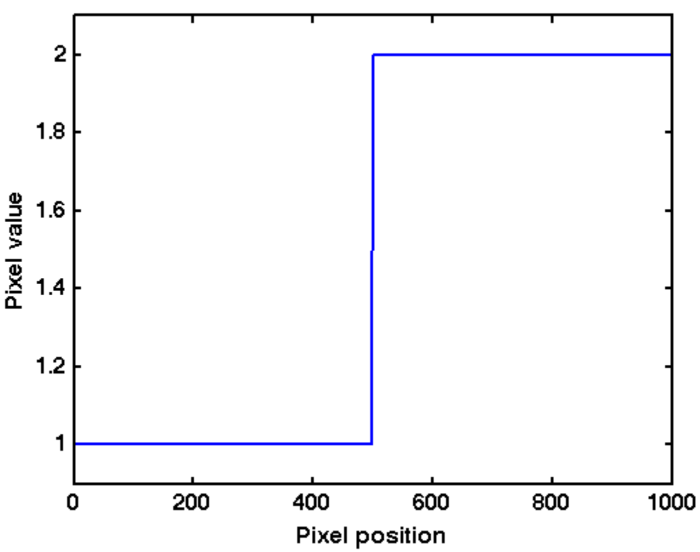
Resolution and sampling rate

- Pixels per inch [ppi]
  - Does not account for vision
- The visual resolution depends on
  - screen size
  - screen resolution
  - viewing distance
- The right measure
  - Pixels per visual degree [ppd]
  - In frequency space
    - Cycles per visual degree [cpd]

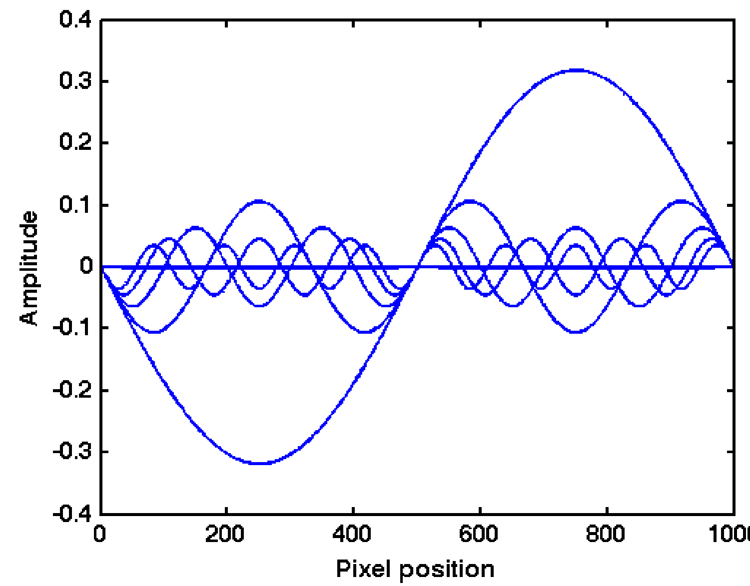


Fourier analysis

- Every N-dimensional function (including images) can be represented as a sum of sinusoidal waves of different frequency and phase



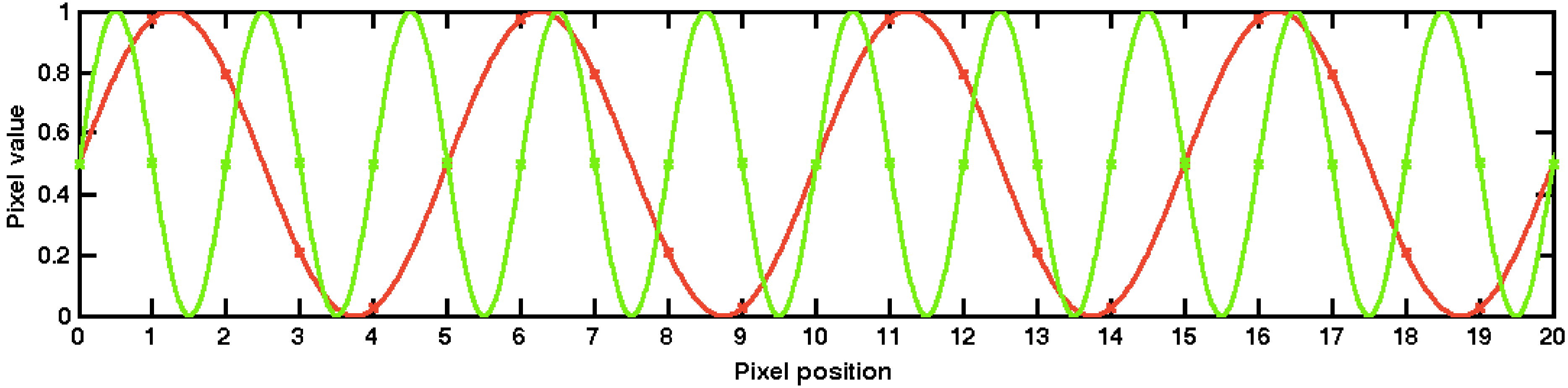
=å



- Think of "equalizer" in audio software, which manipulates each frequency

Spatial frequency in images

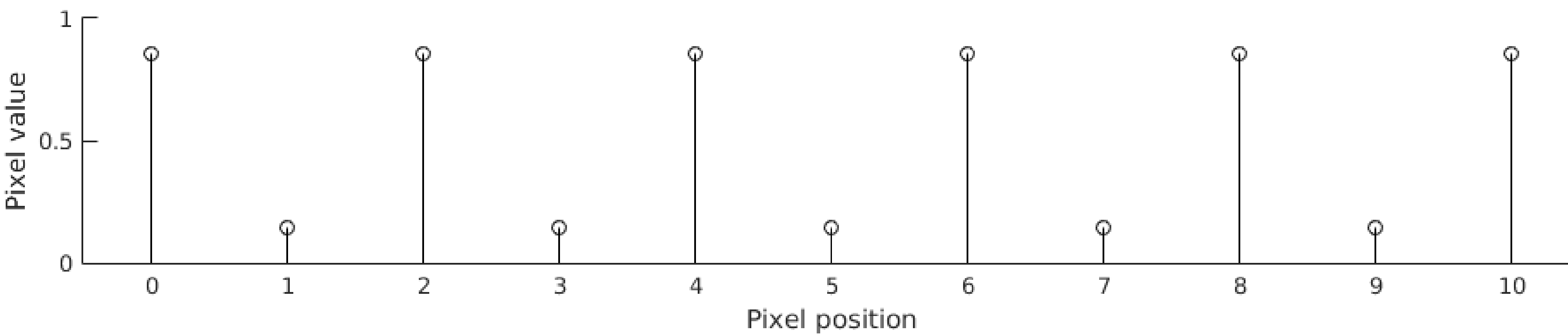
- Image space units: cycles per sample (or cycles per pixel)



  - What are the screen-space frequencies of the red and green sinusoid?
- The visual system units: cycles per degree
  - If the angular resolution of the viewed image is 55 pixels per degree, what is the frequency of the sinusoids in cycles per degree?

Nyquist frequency

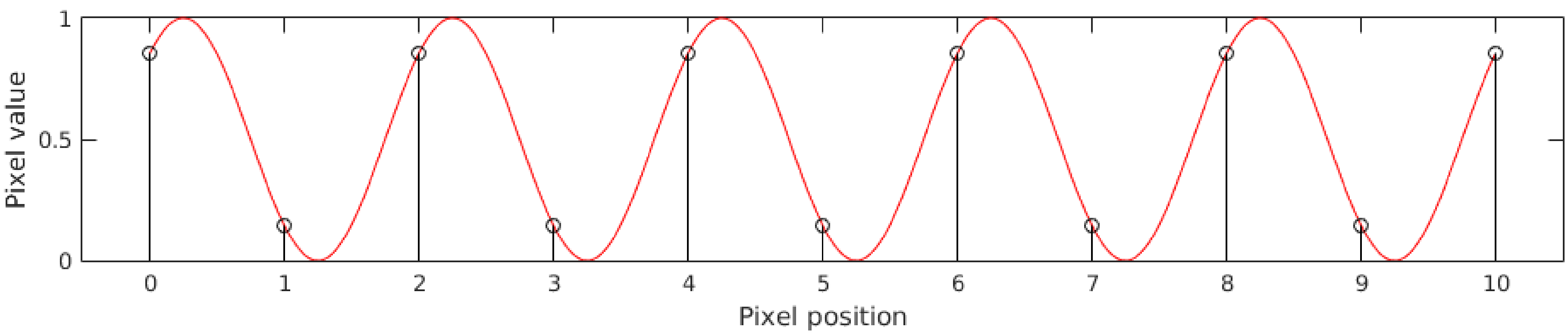
- Sampling density restricts the highest spatial frequency signal that can be (uniquely) reconstructed
  - Sampling density – how many pixels per image/visual angle/…



  - Any number of sinusoids can be fitted to this set of samples
  - It is possible to fit an infinite number of sinusoids if we allow infinitely high frequency

Nyquist frequency

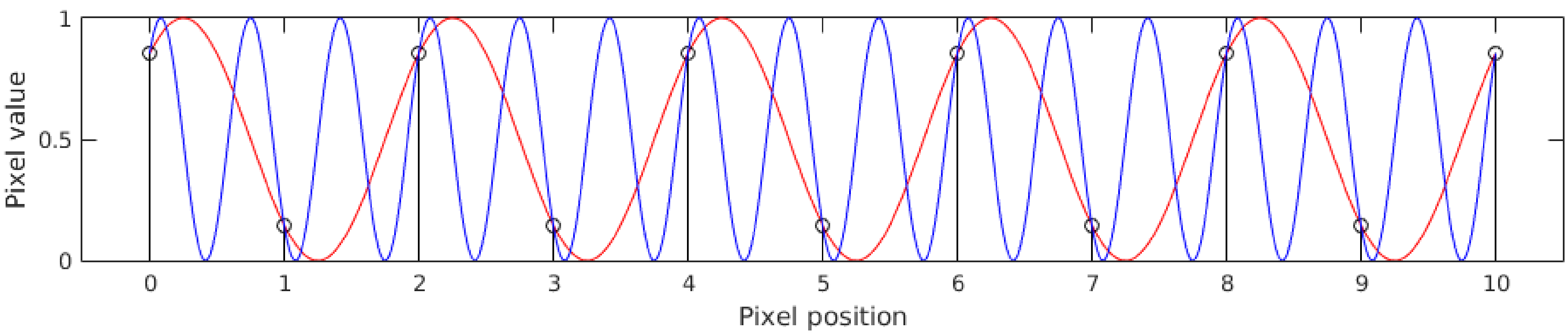
- Sampling density restricts the highest spatial frequency signal that can be (uniquely) reconstructed
  - Sampling density – how many pixels per image/visual angle/…



  - Any number of sinusoids can be fitted to this set of samples
  - It is possible to fit an infinite number of sinusoids if we allow infinitely high frequency

Nyquist frequency

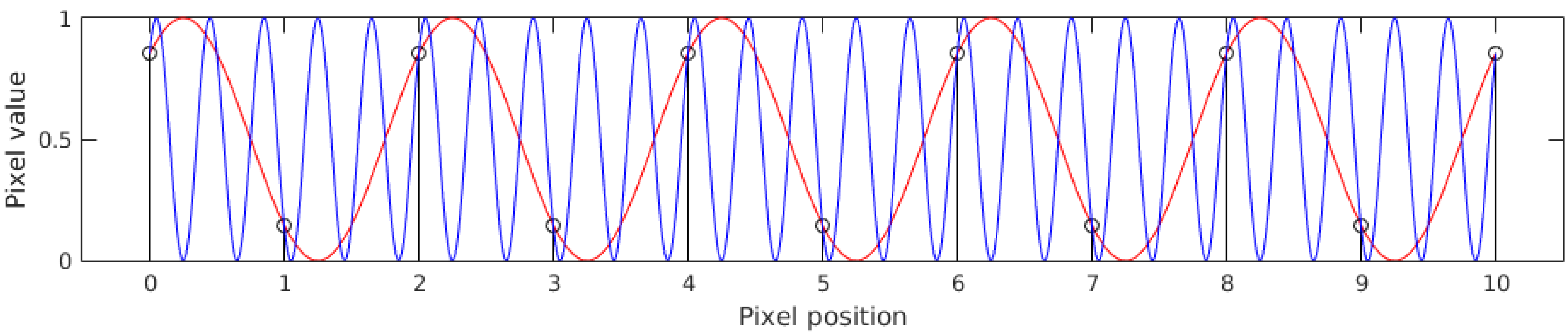
- Sampling density restricts the highest spatial frequency signal that can be (uniquely) reconstructed
  - Sampling density – how many pixels per image/visual angle/…



  - Any number of sinusoids can be fitted to this set of samples
  - It is possible to fit an infinite number of sinusoids if we allow infinitely high frequency

Nyquist frequency

- **Sampling density restricts the highest spatial frequency signal that can be (uniquely) reconstructed**
  - Sampling density – how many pixels per image/visual angle/…

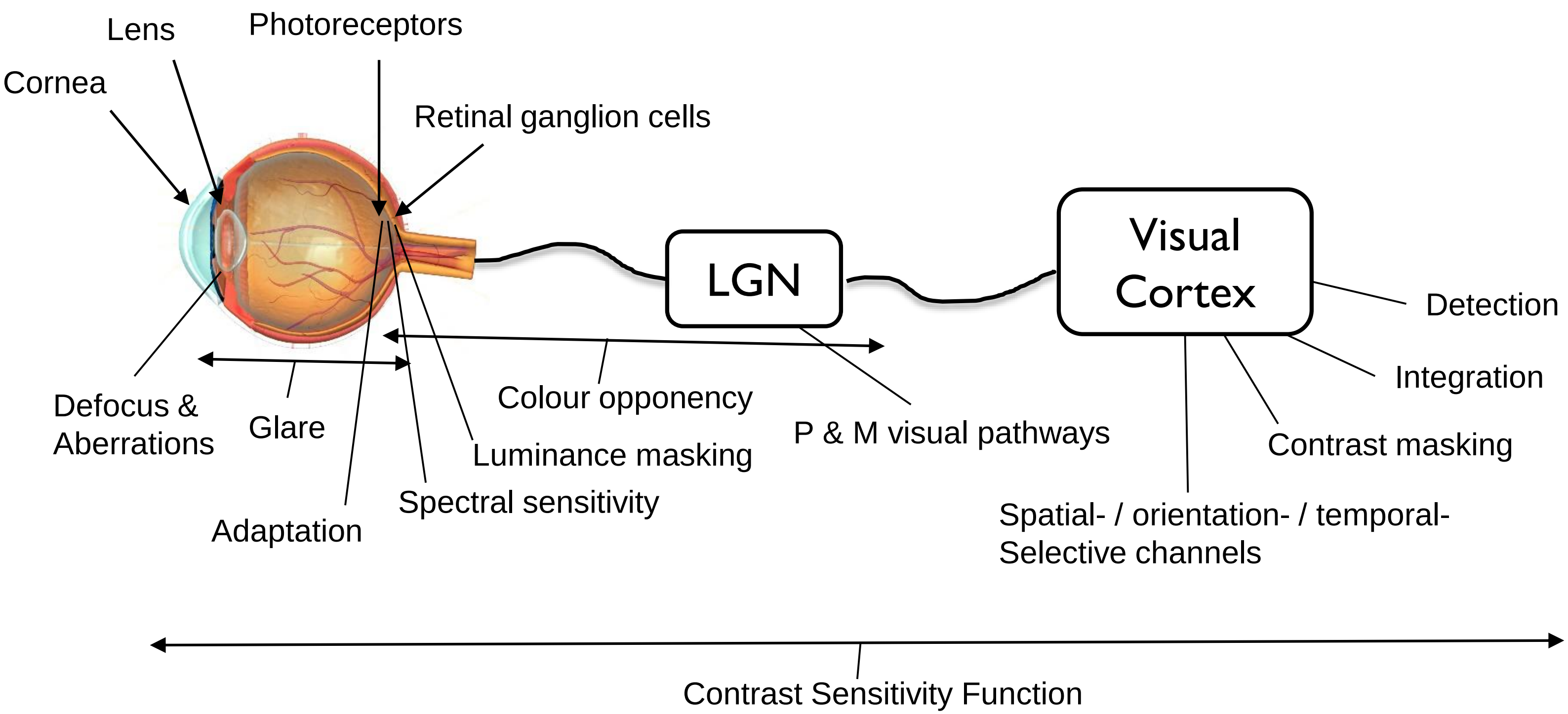


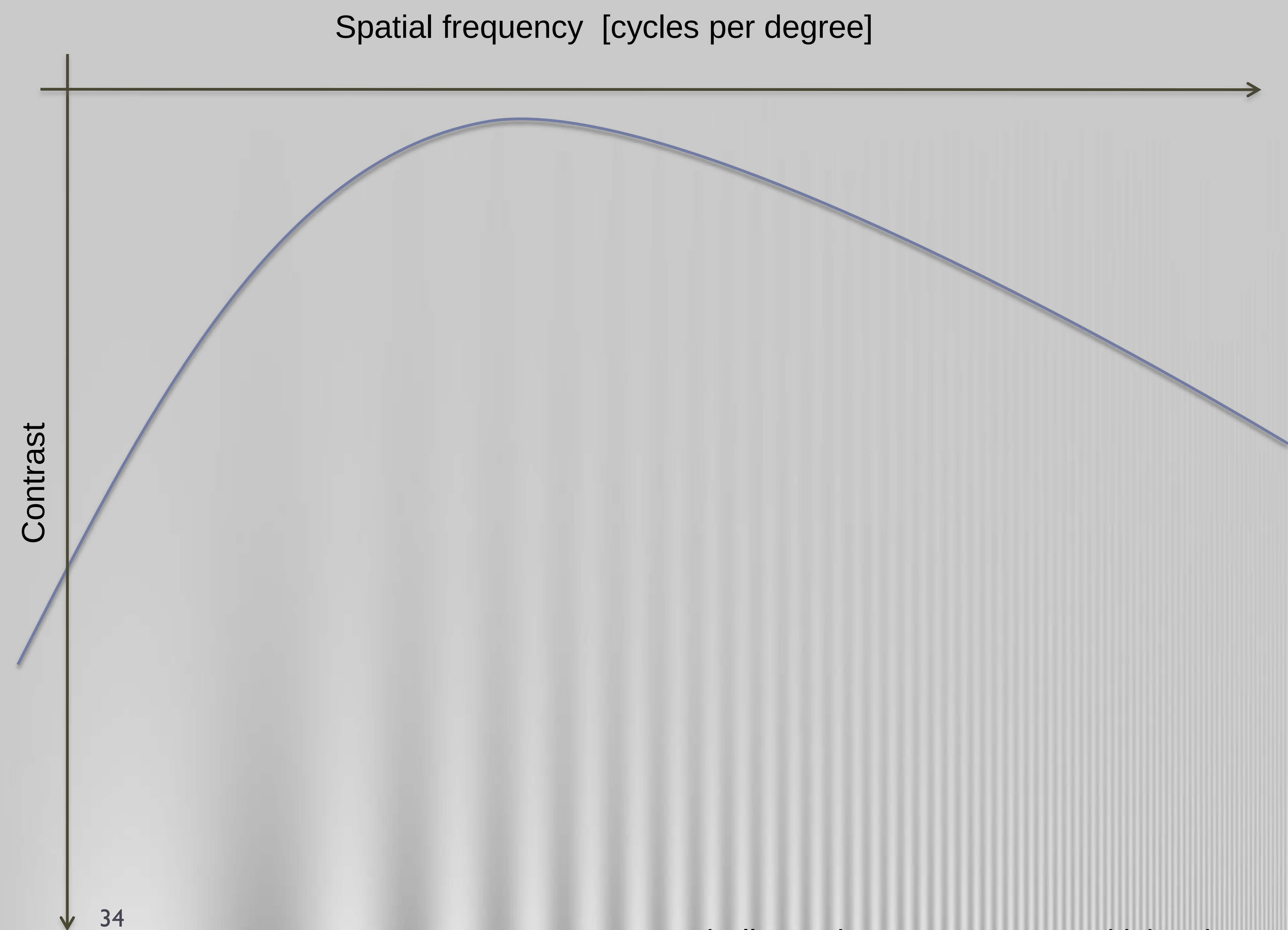
  - Any number of sinusoids can be fitted to this set of samples
  - It is possible to fit an infinite number of sinusoids if we allow infinitely high frequency

Nyquist frequency / aliasing

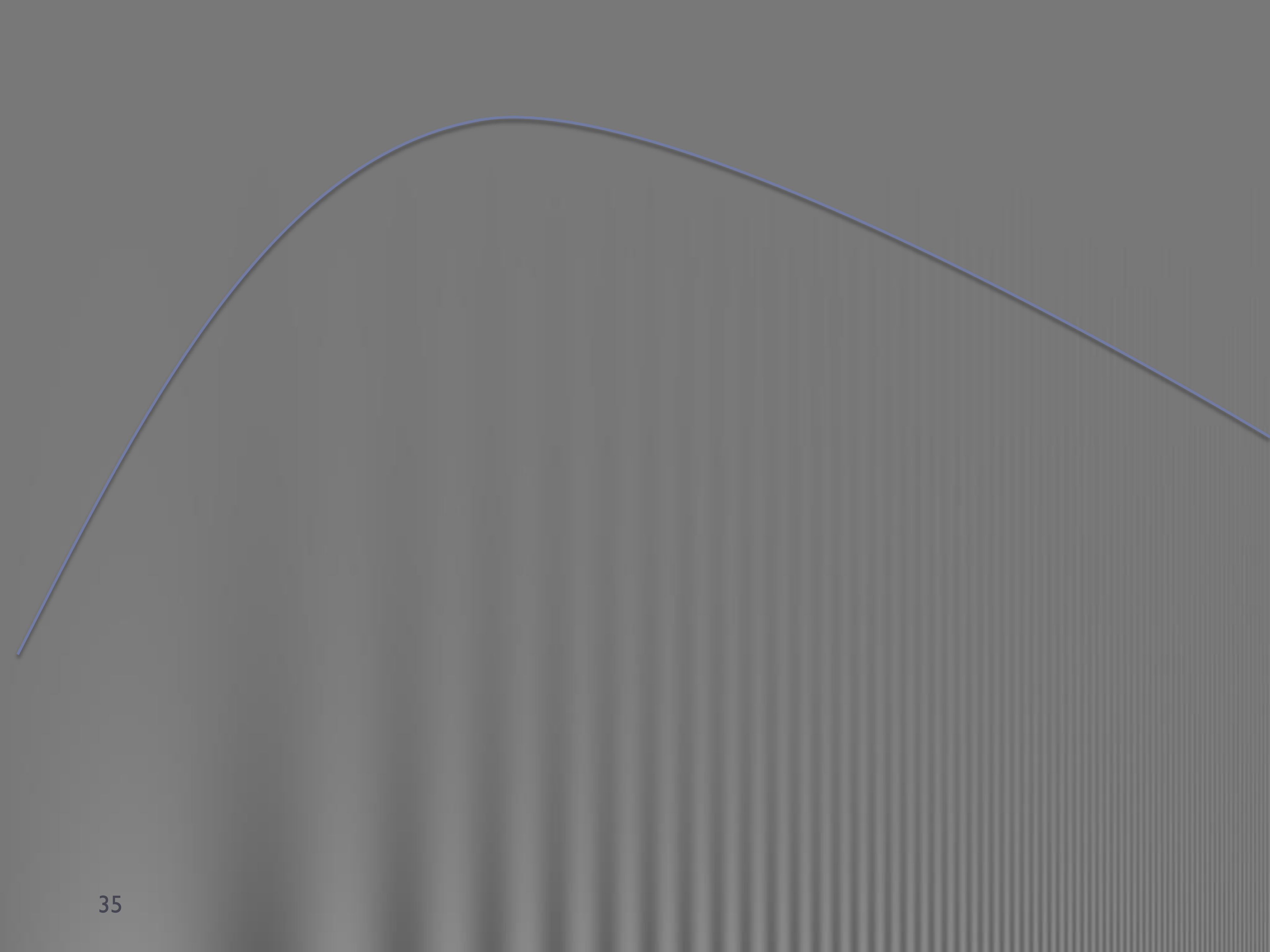
- Nuquist frequency is the highest frequency that can be represented by a discrete set of uniform samples (pixels)
- Nuquist frequency = 0.5 sampling rate
  - For audio
    - If the sampling rate is 44100 samples per second (audio CD), then the Nyquist frequency is 22050 Hz
  - For images (visual degrees)
    - If the sampling rate is 60 pixels per degree, then the Nyquist frequency is 30 cycles per degree
- When resampling an image to lower resolution, the frequency content above the Nyquist frequency needs to be removed (reduced in practice)
  - Otherwise **aliasing** is visible

Modeling contrast detection

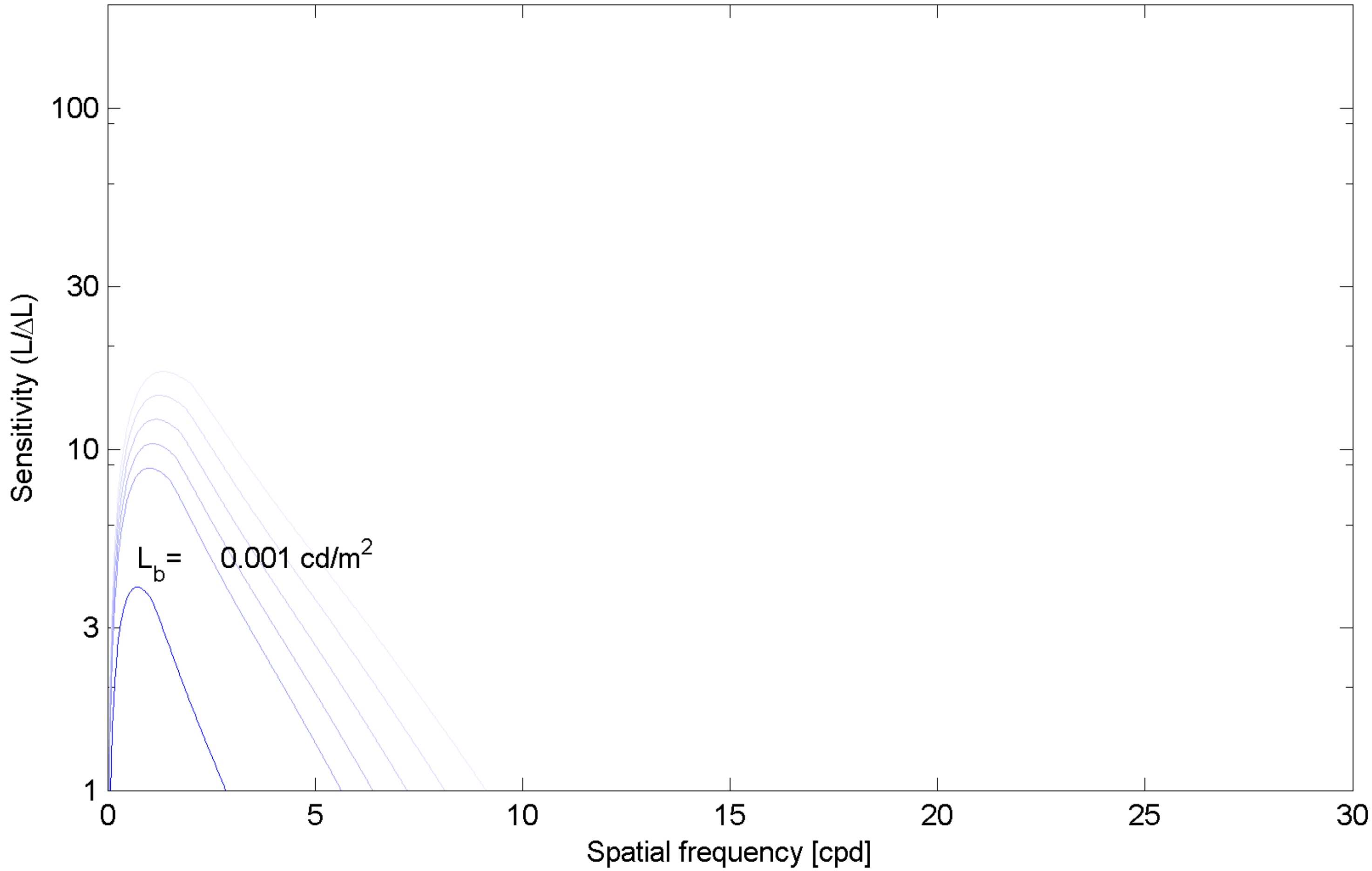




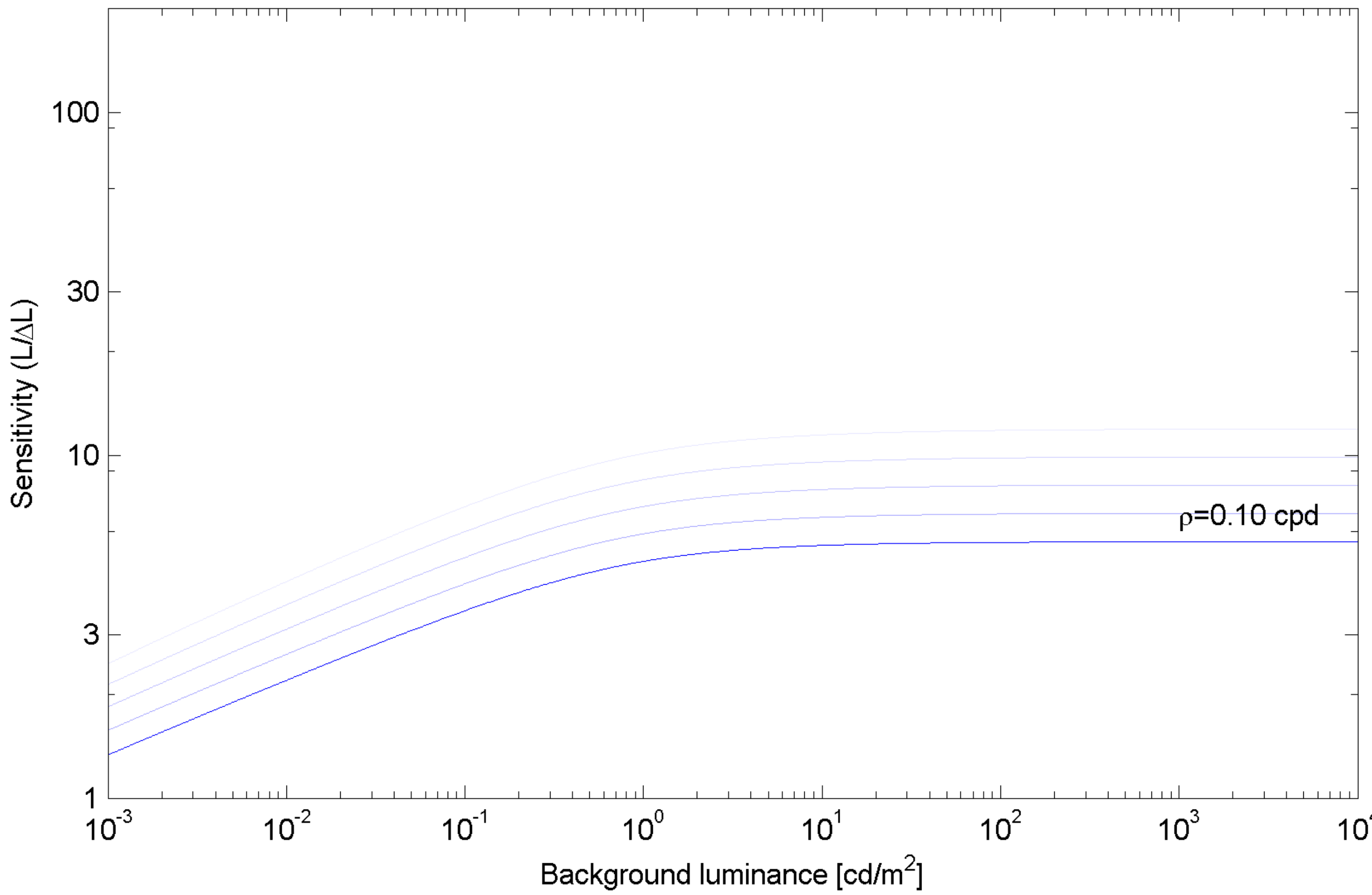
Campbell & Robson contrast sensitivity chart



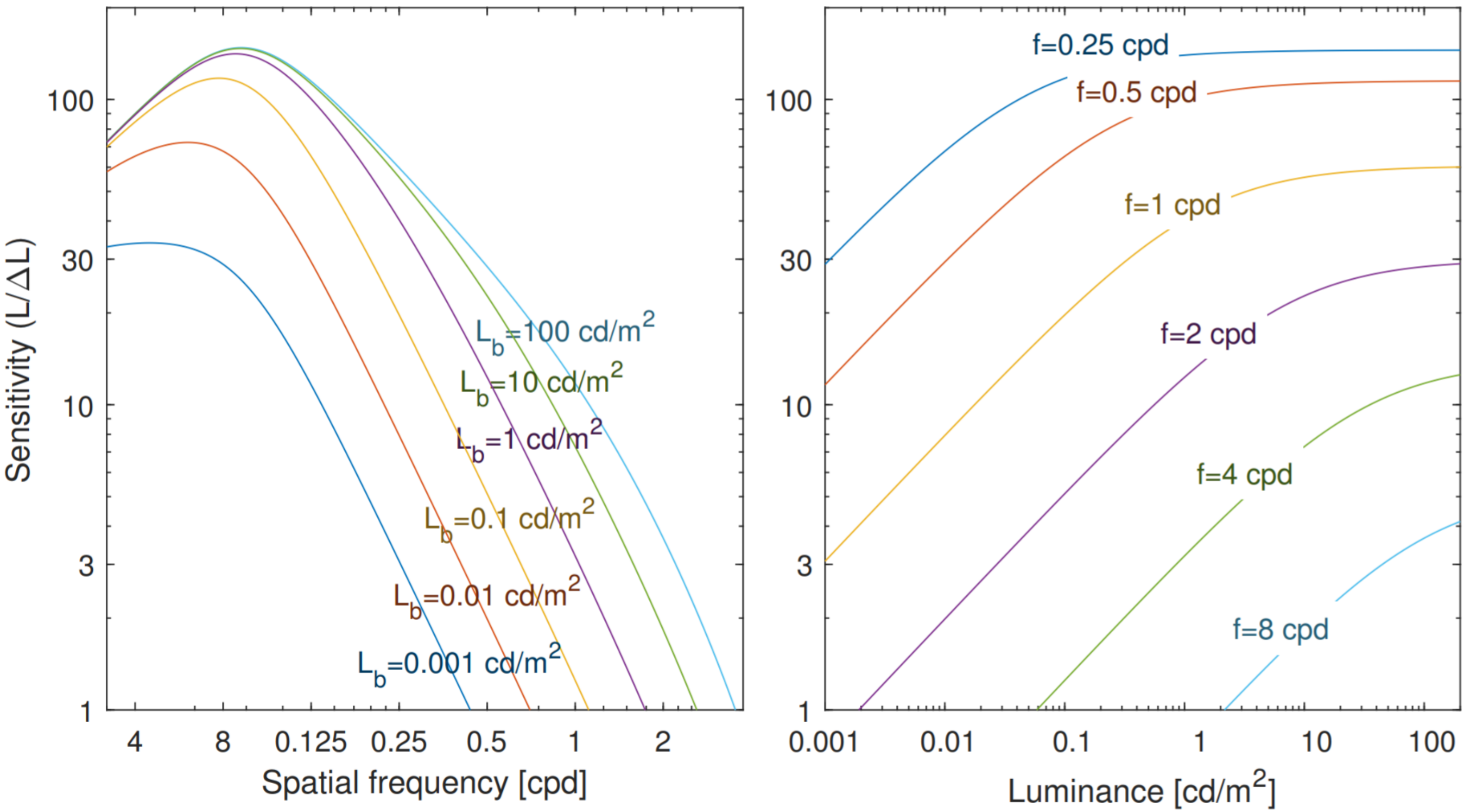
CSF as a function of spatial frequency



CSF as a function of background luminance



CSF as a function of spatial frequency and background luminance



Contrast constancy

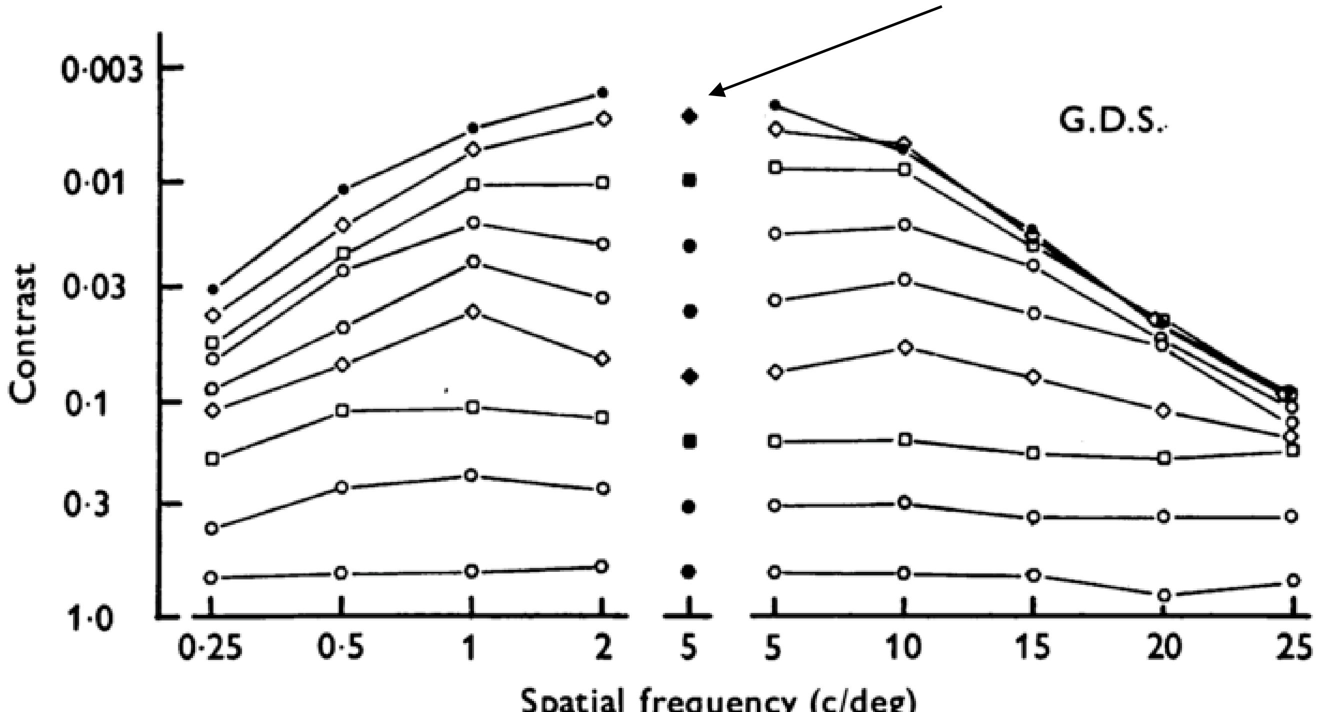
Contrast constancy

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

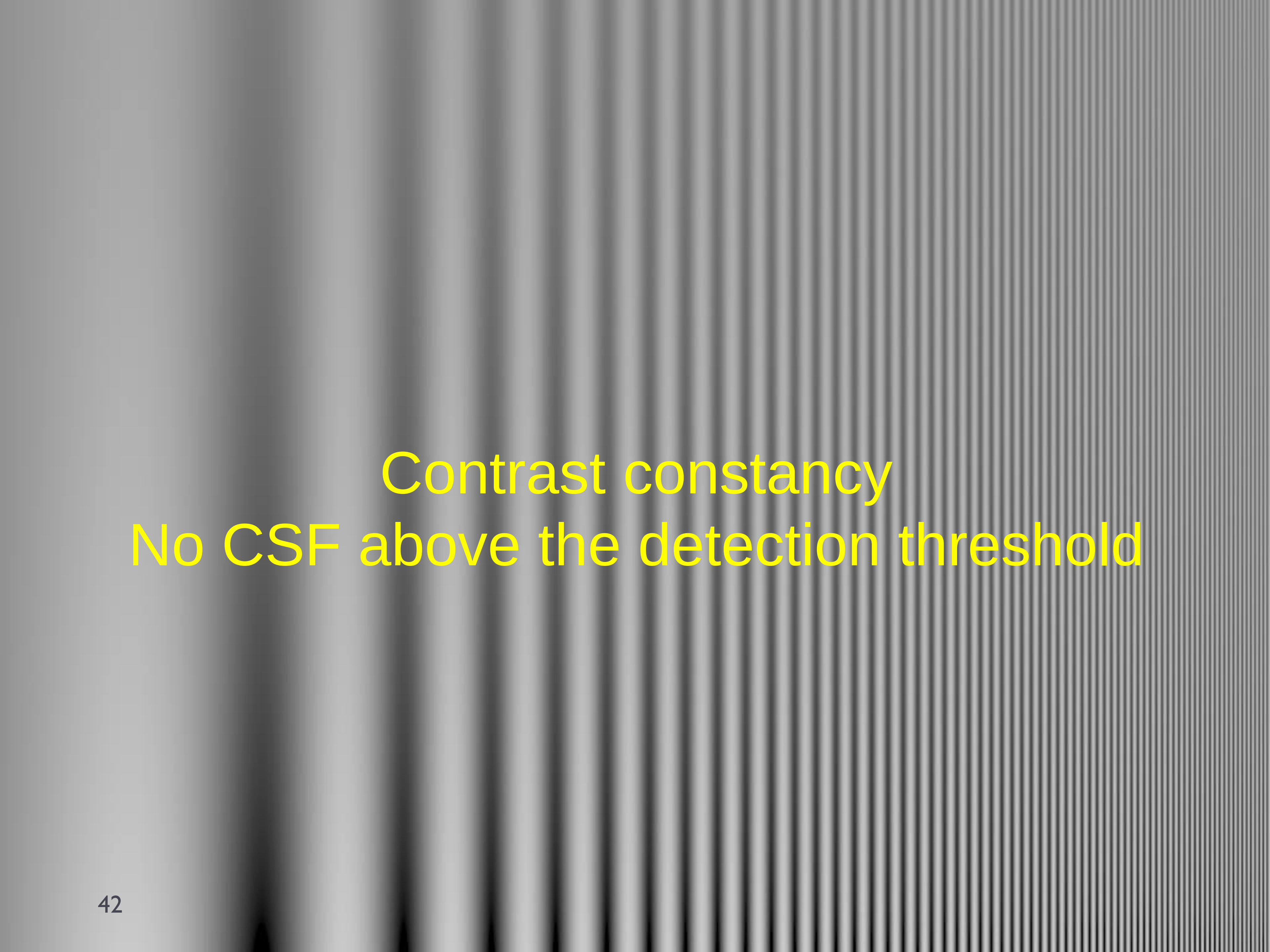
Test

Match?

Reference

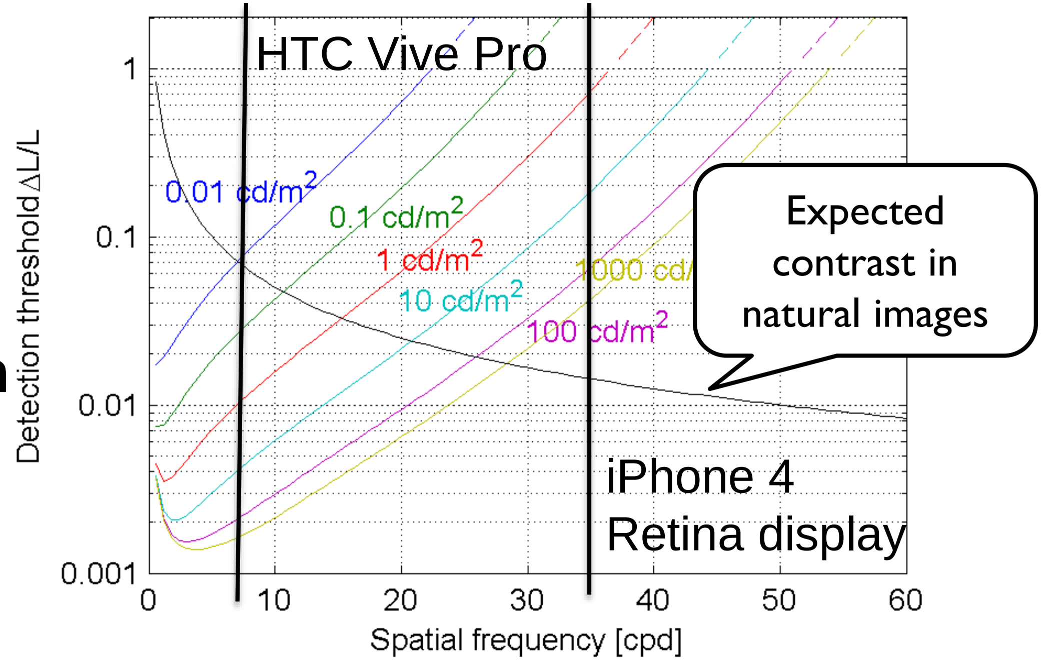


From: Georgeson and Sullivan. 1975. J. Phsysio.


Contrast constancy
No CSF above the detection threshold

CSF and the resolution

- CSF plotted as the detection contrast
$$\frac{\Delta L}{L_b} = S^{-1}$$
- The contrast below each line is invisible
- Maximum perceivable resolution depends on luminance

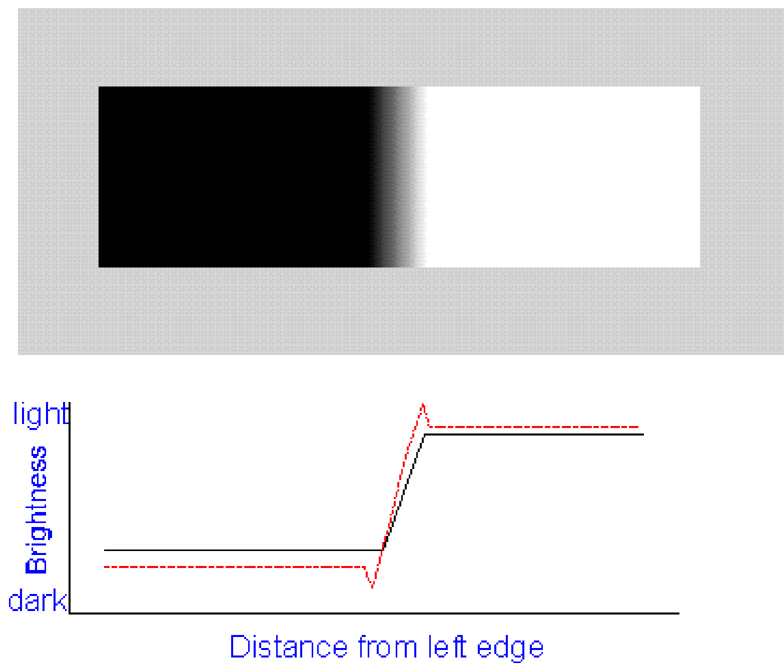


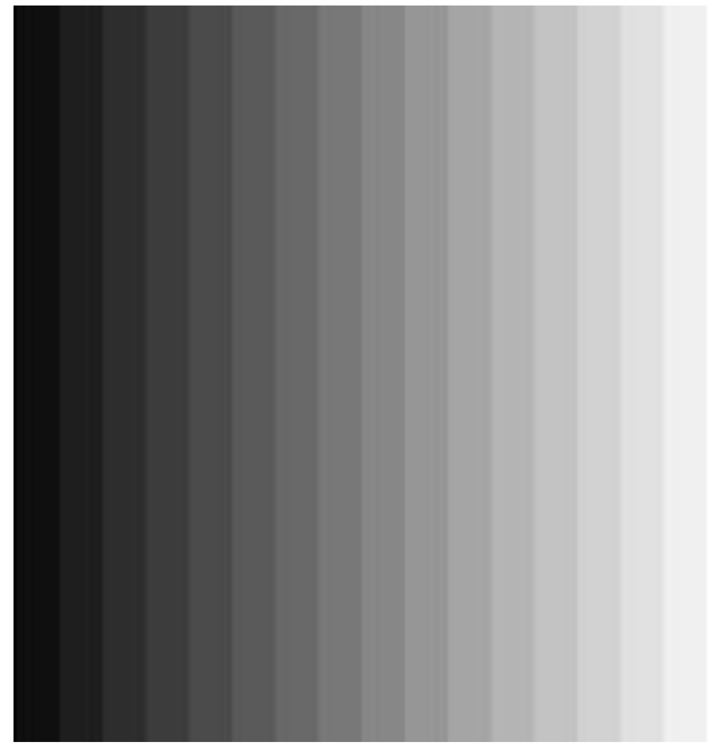
CSF models:
Barten, P. G. J. (2004).
https://doi.org/10.1117/12.537476

Lateral inhibition and Multi-resolution models

Mach Bands – evidence for band-pass visual processing

- "Overshooting" along edges
  - Extra-bright rims on bright sides
  - Extra-dark rims on dark sides
- Due to "Lateral Inhibition"

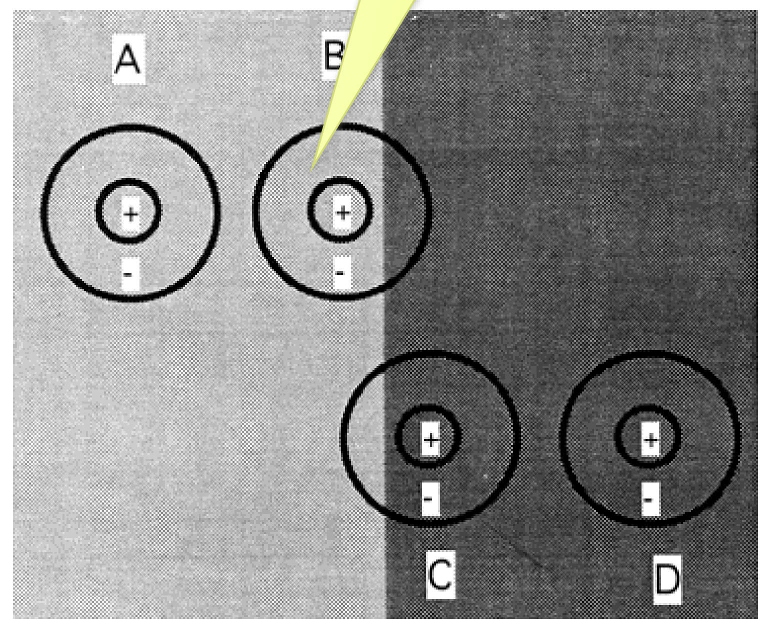


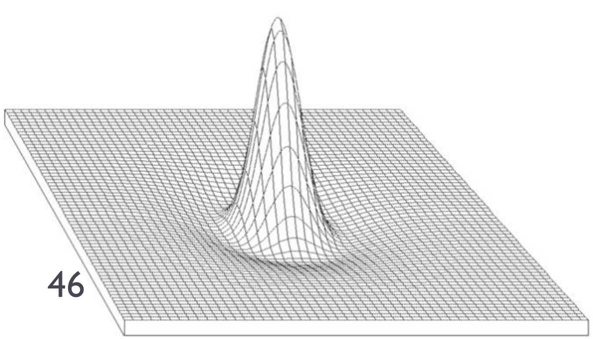


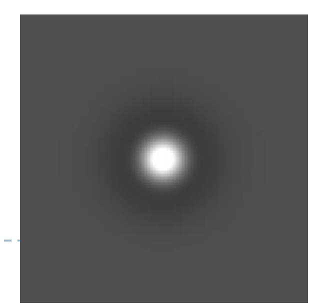
Centre-surround (Lateral Inhibition)

- "Pre-processing" step within the retina
  - Surrounding brightness level weighted negatively
    - A: high stimulus, maximal bright inhibition
    - B: high stimulus, reduced inhibition & stronger response
    - D: low stimulus, maximal inhibition
    - C: low stimulus, increased inhibition & weaker response

Center-surround receptive fields (groups of photoreceptors)







Centre-surround: Hermann Grid

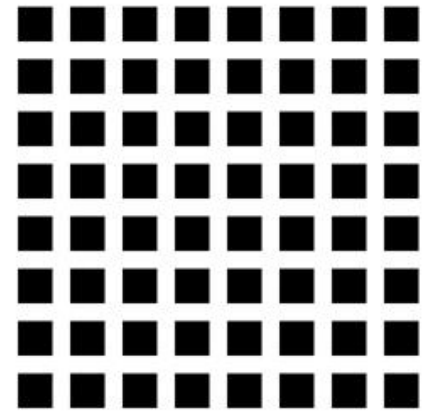
- Dark dots at crossings
- Explanation
  - Crossings (A)
    - More surround stimulation (more bright area)

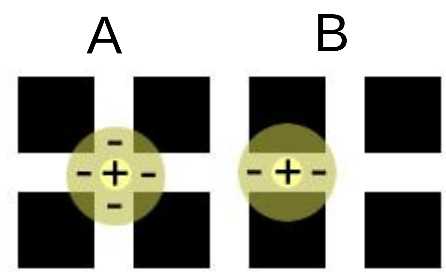
    ⇒ Less inhibition

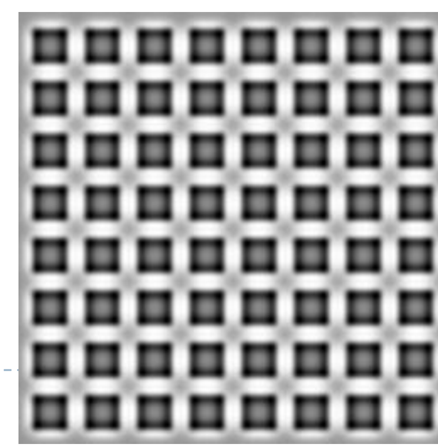
    ⇒ Weaker response
  - Streets (B)
    - Less surround stimulation

    ⇒ More inhibition

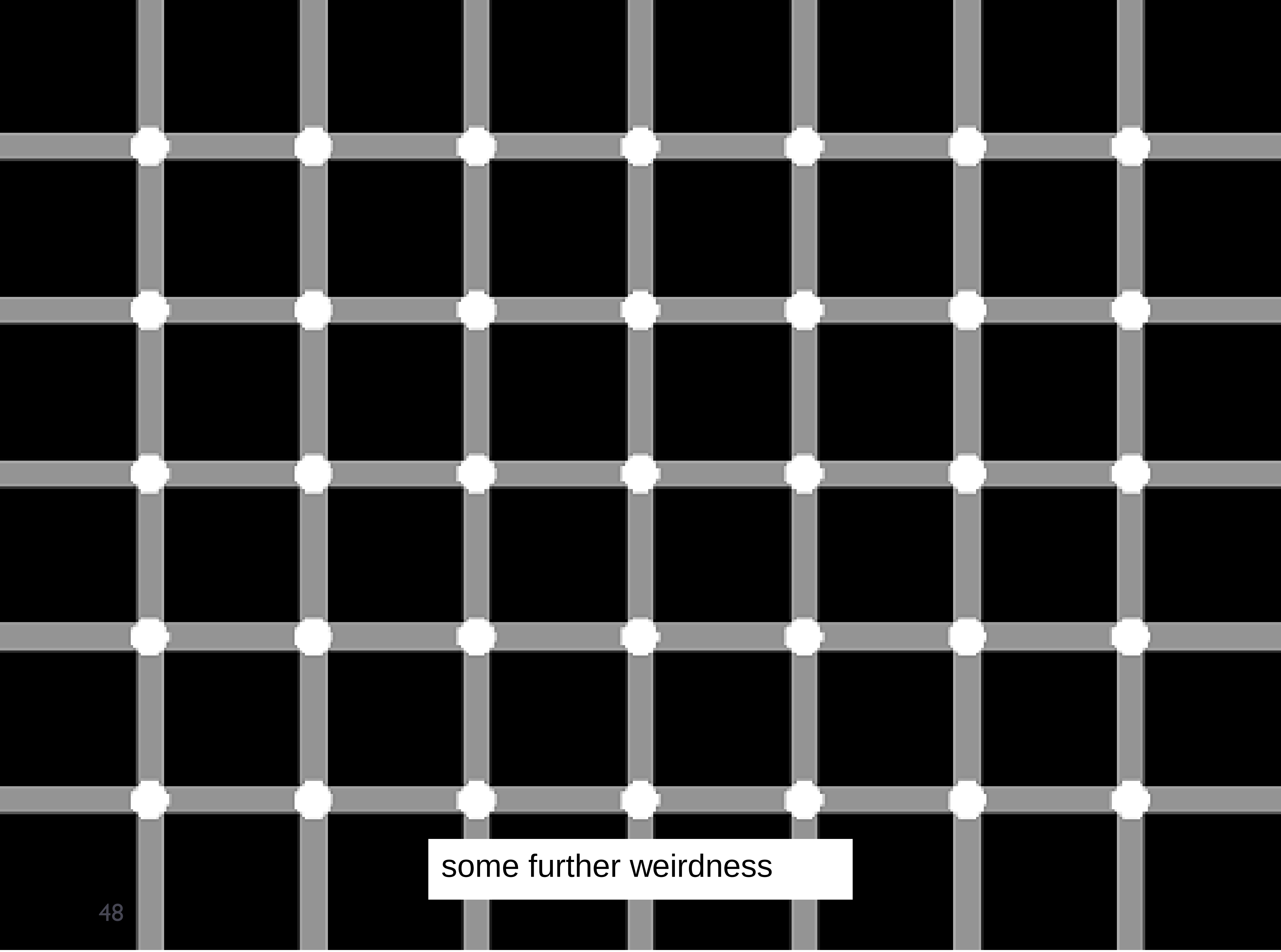
    ⇒ Greater response
- Simulation
  - Darker at crossings, brighter in streets
  - Appears more steady
  - What if reversed ?







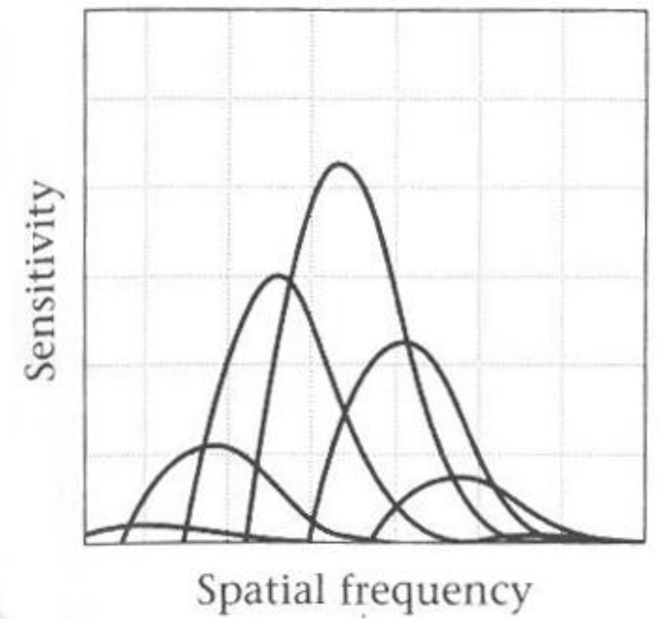
Simulation



some further weirdness

Spatial-frequency selective channels

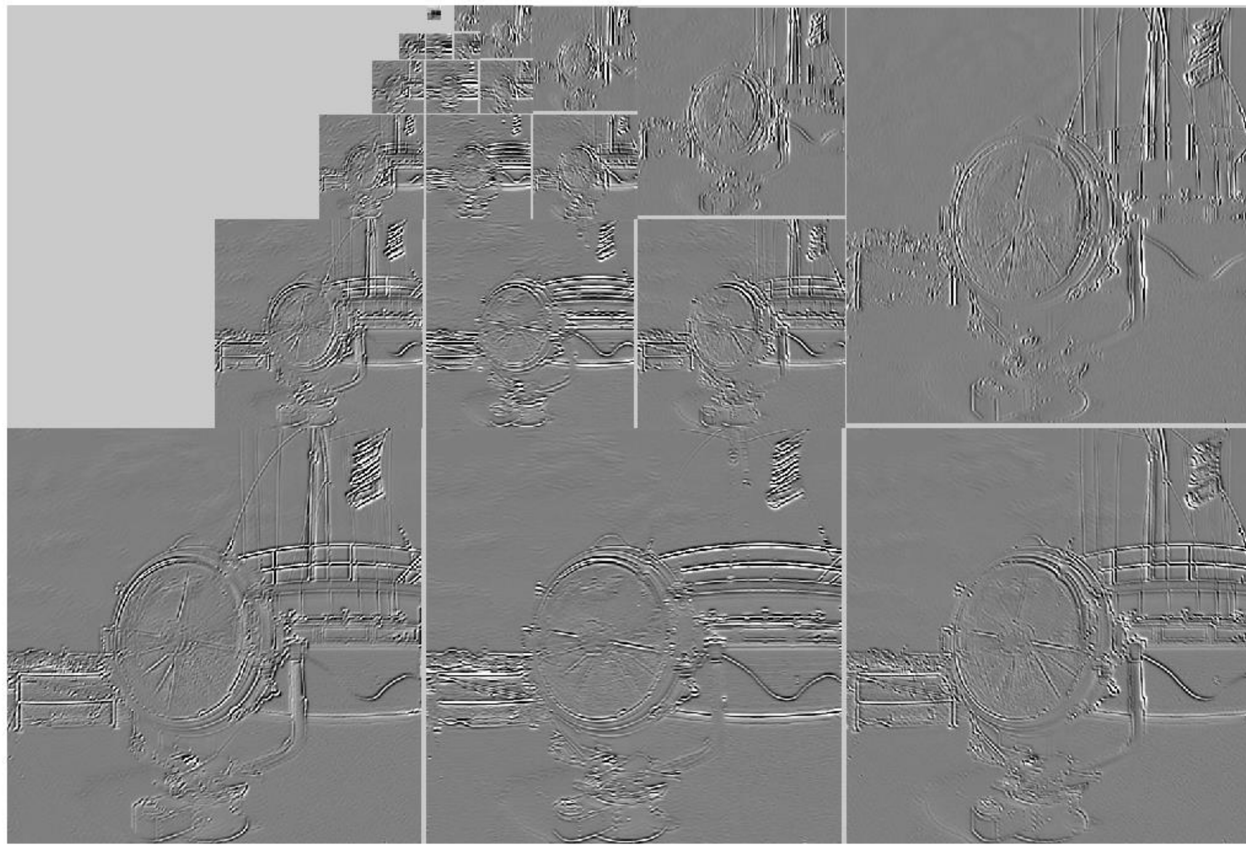
- The visual information is decomposed in the visual cortex into multiple channels
  - The channels are selective to spatial frequency, temporal frequency and orientation
  - Each channel is affected by different „noise" level
  - The CSF is the net result of information being passed in noise-affected visual channels



From: Wandell, 1995

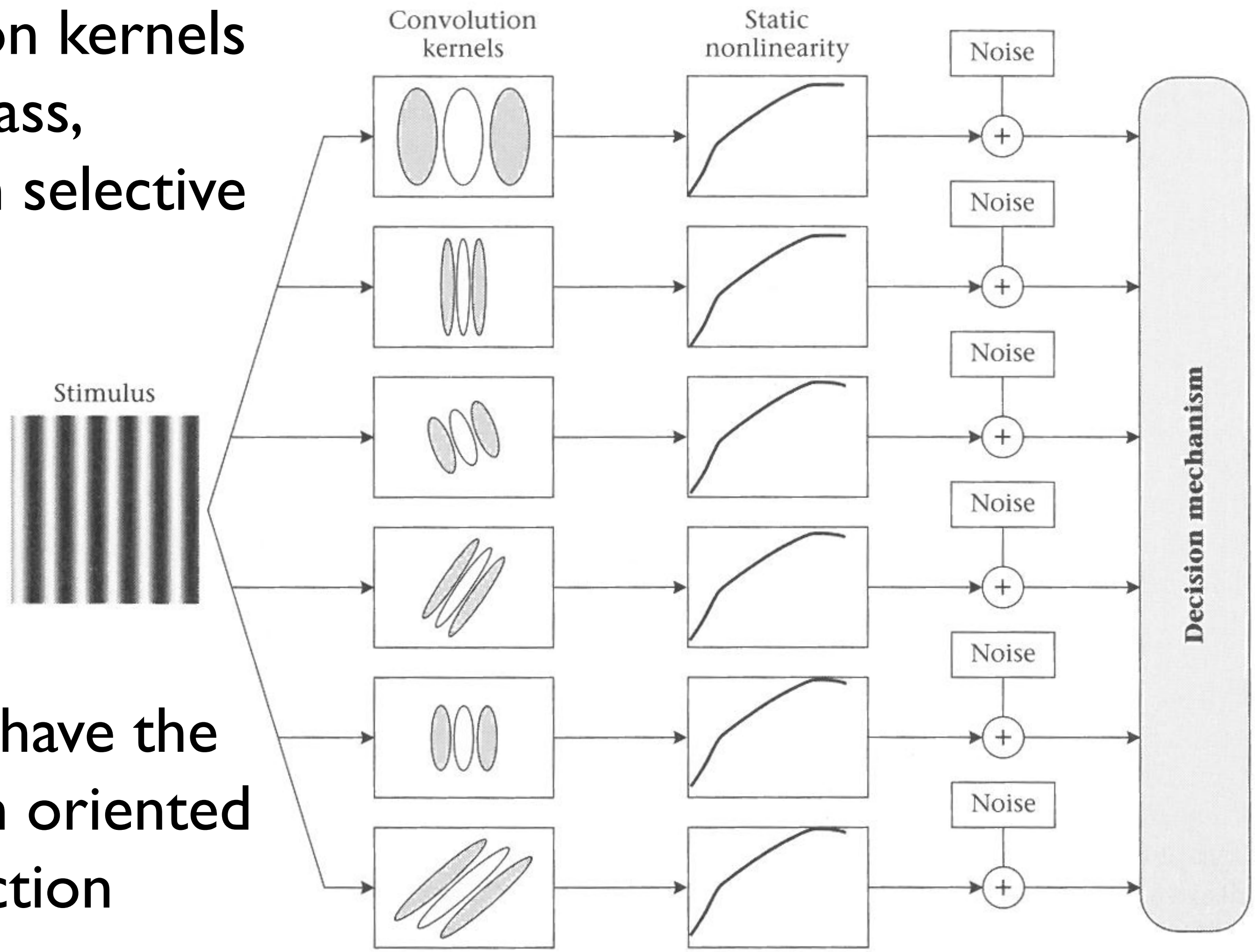
Multi-scale decomposition

Steerable pyramid decomposition



Multi-resolution visual model

- Convolution kernels are band-pass, orientation selective filters



- The filters have the shape of an oriented Gabor function

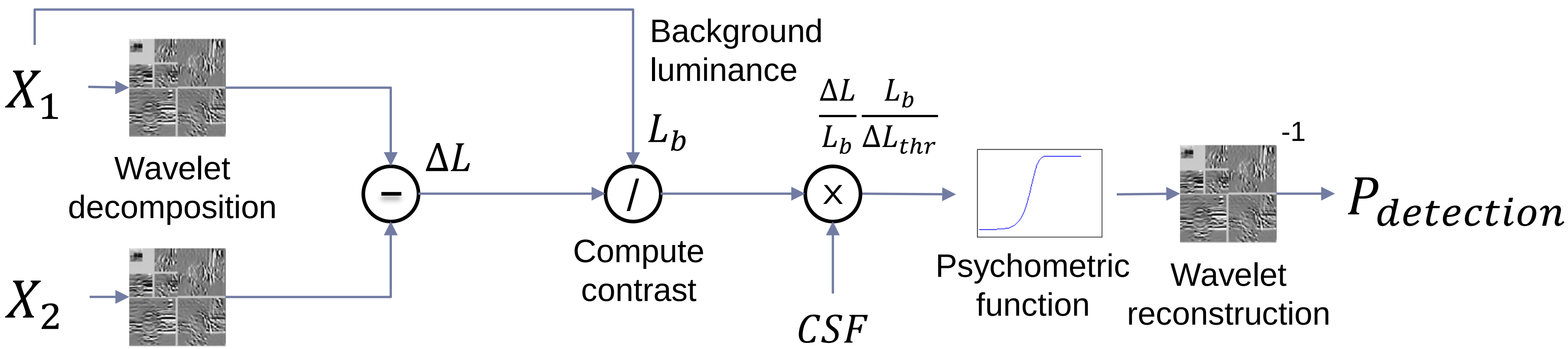
From: Wandell, 1995

Predicting visible differences with CSF

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

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

$f[X]$ The percept of image X

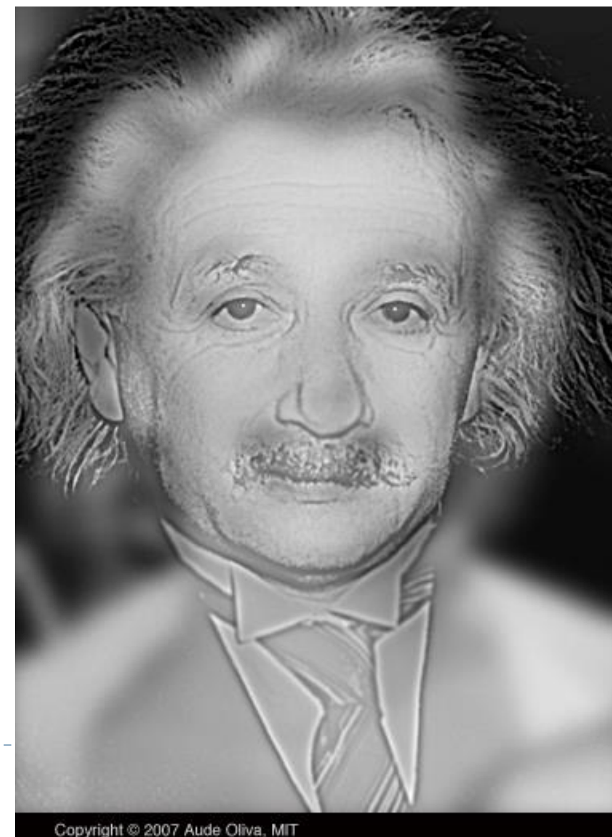


(simplified) Visual Difference Predictor

Daly, S. (1993).

Applications of multi-scale models

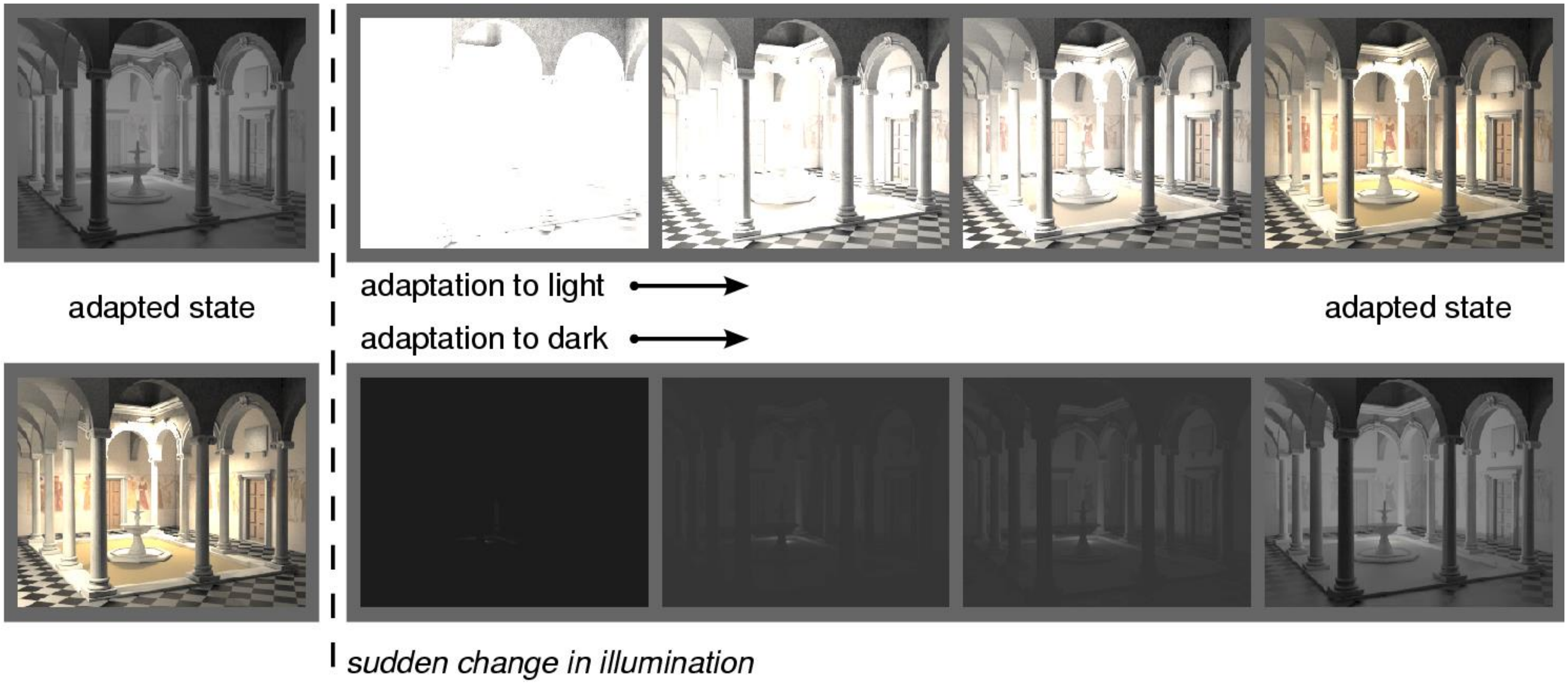
- JPEG2000
  - Wavelet decomposition
- JPEG / MPEG
  - Frequency transforms
- Image pyramids
  - Blending & stitching
  - Hybrid images



Hybrid Images by Aude Oliva
http://cvcl.mit.edu/hybrid_gallery

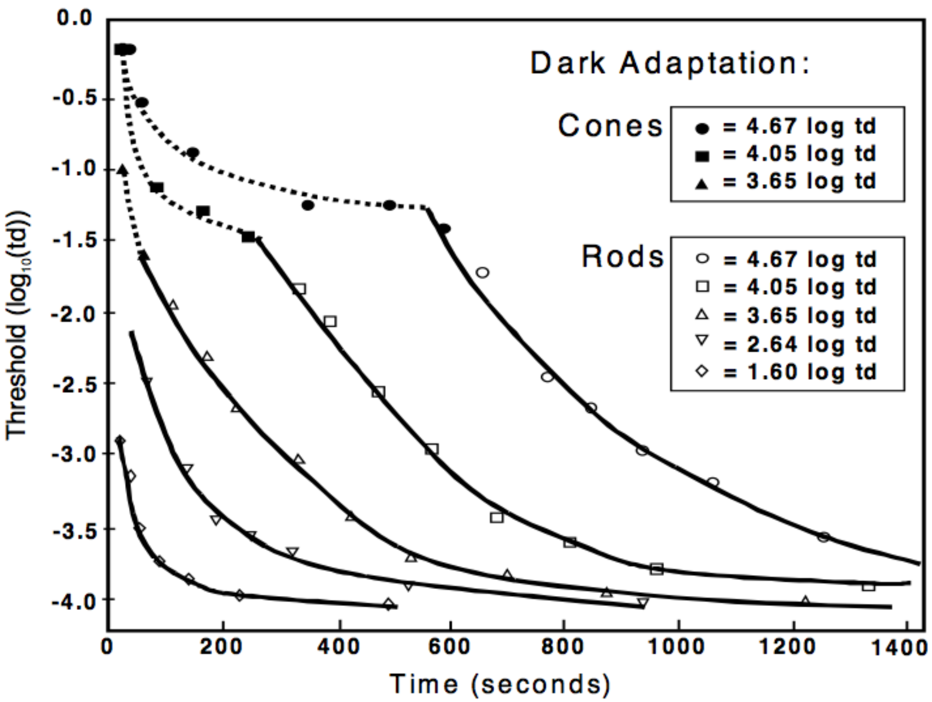
Light and dark adaptation

Light and dark adaptation

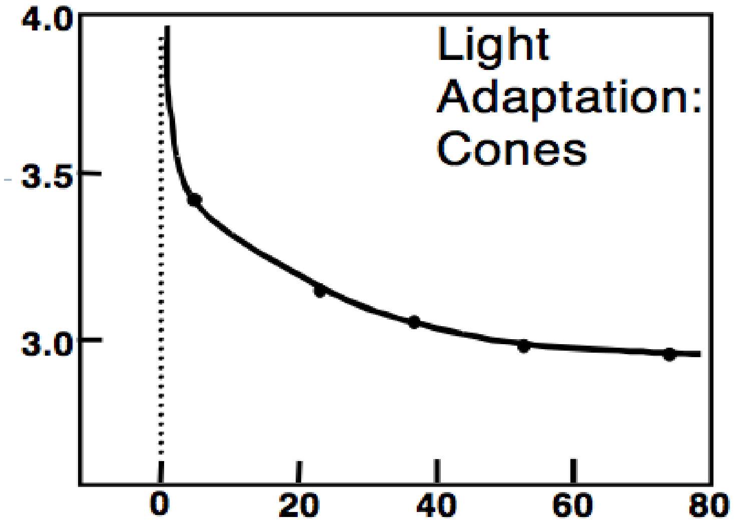


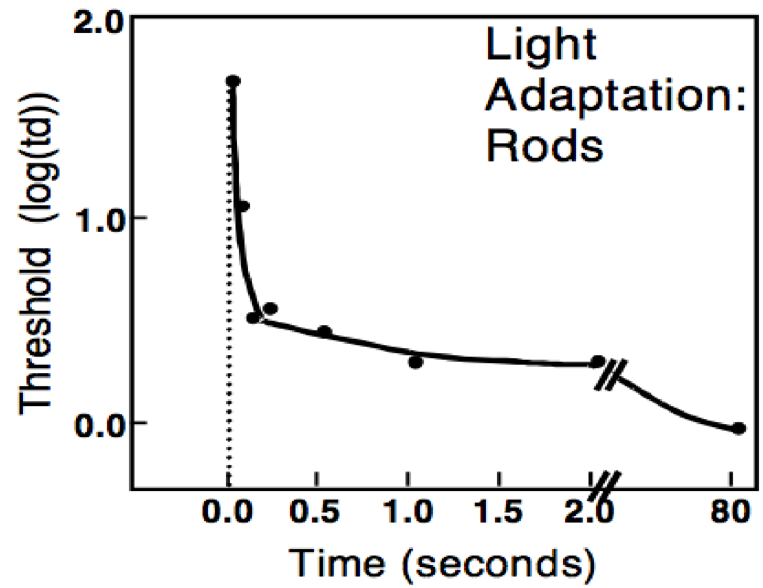
- Light adaptation: from dark to bright
- Dark adaptation: from bright to dark (much slower)

Time-course of adaptation



Bright -> Dark





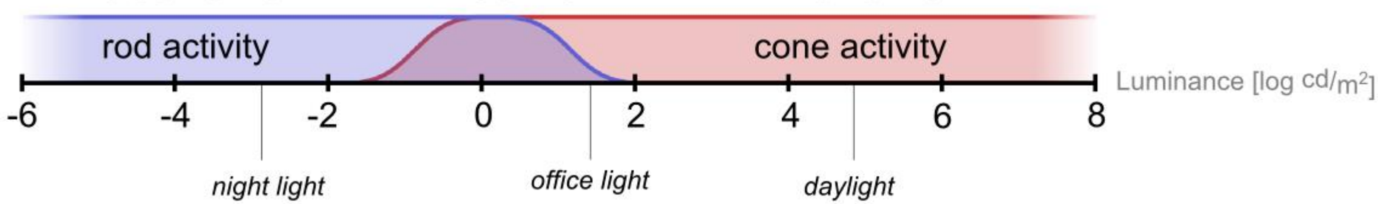
Dark -> Bright

Temporal adaptation mechanisms

- Bleaching & recovery of photopigment
  - Slow assymetric (light -> dark, dark -> light)
  - Reaction times (1-1000 sec)
  - Separate time-course for rods and cones
- Neural adaptation
  - Fast
  - Approx. symmetric reaction times (10-3000 ms)
- Pupil
  - Diameter varies between 3 and 8 mm
  - About 1:7 variation in retinal illumunation

Night and daylight vision

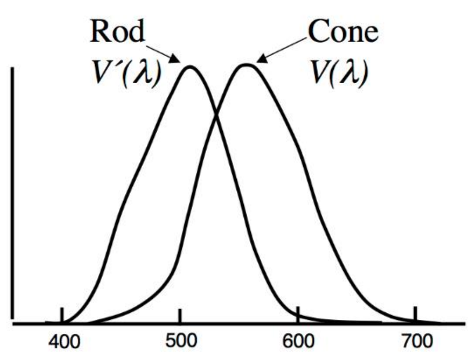
Vision mode:



Mode properties: monochromatic vision
limited visual acuity

good color perception
good visual acuity

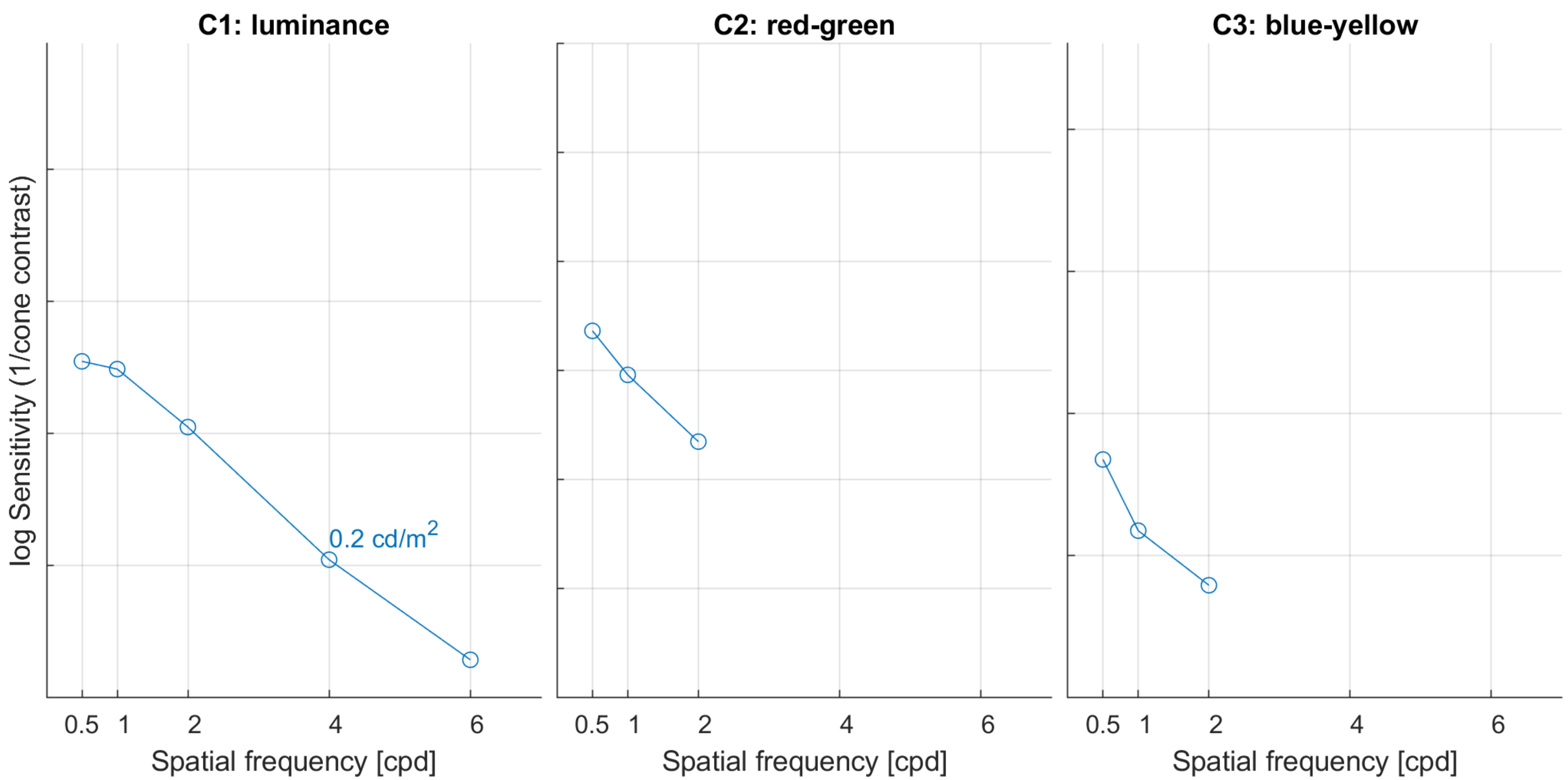
Luminous efficiency



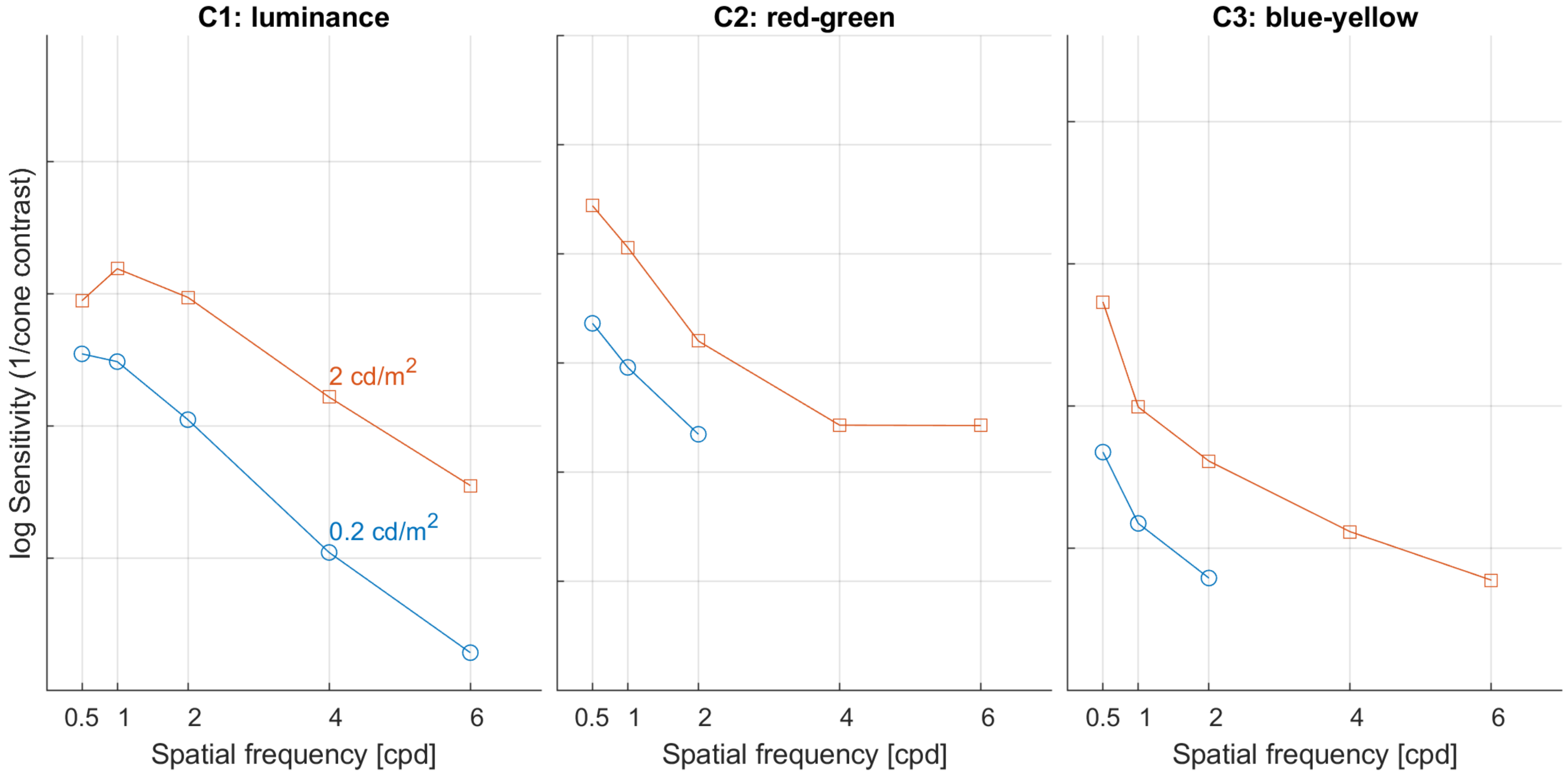
Spatial colour vision

Spatio-chromatic CSF

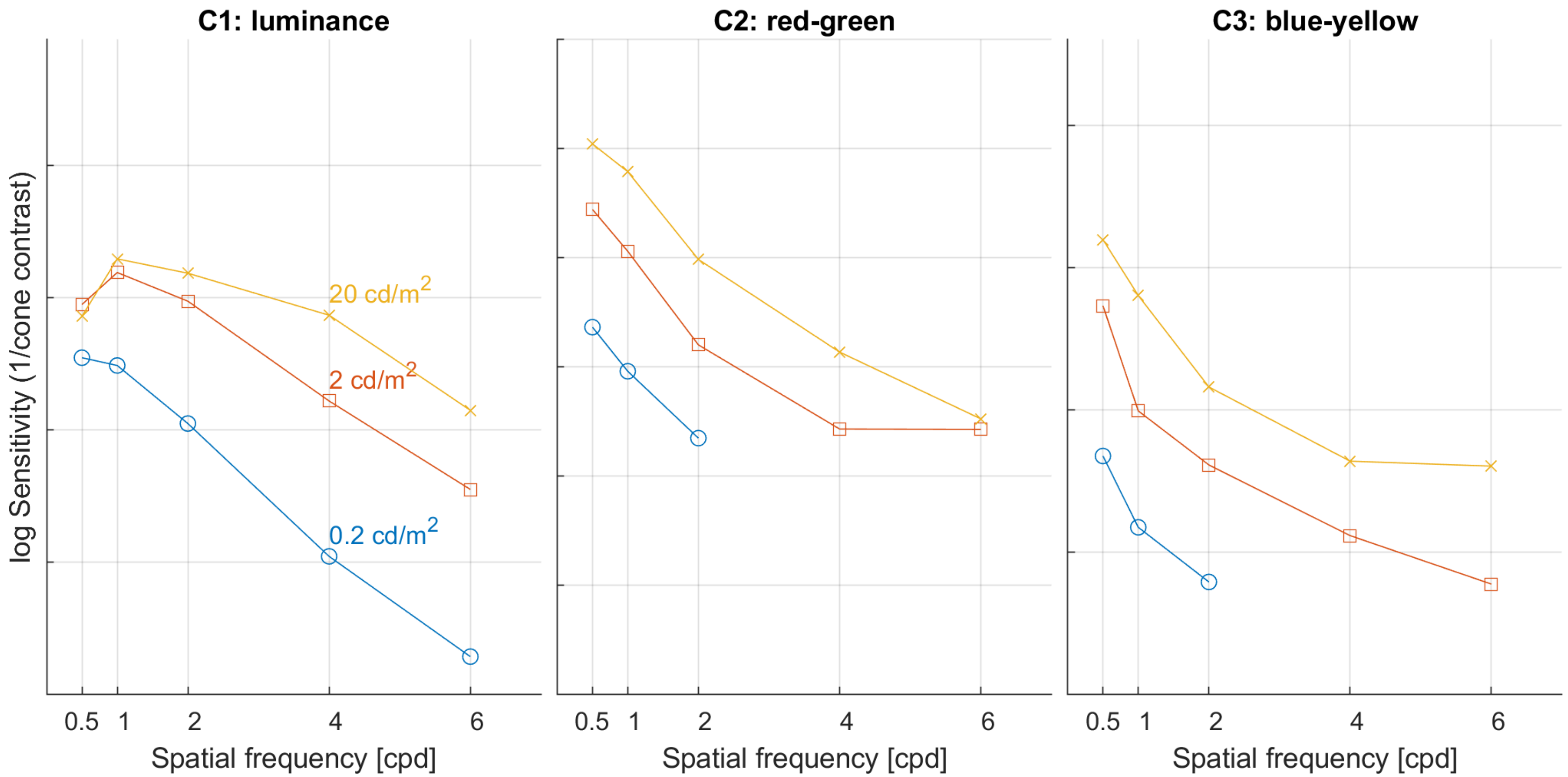
Color CSF across the luminance range



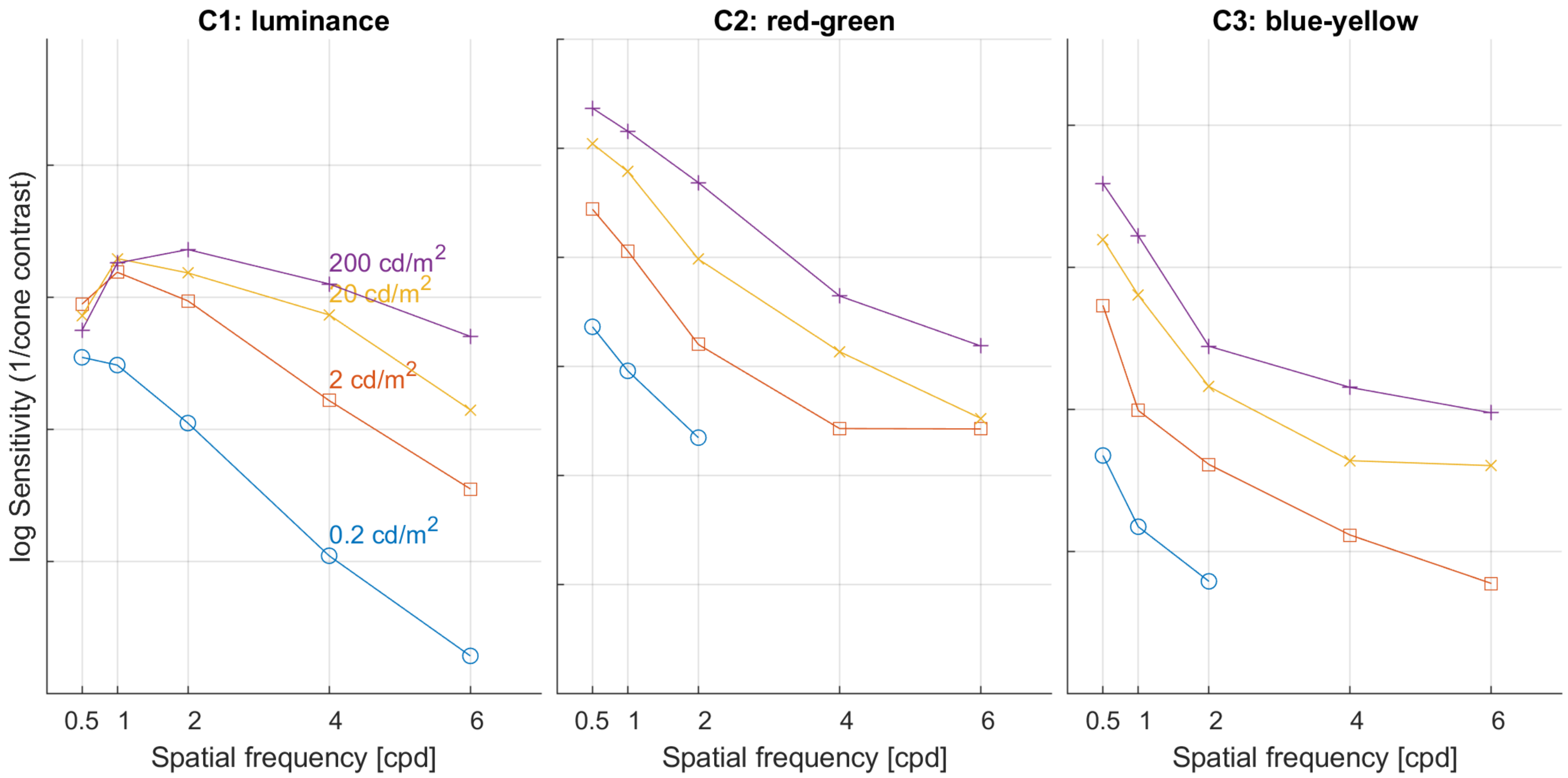
Color CSF across the luminance range



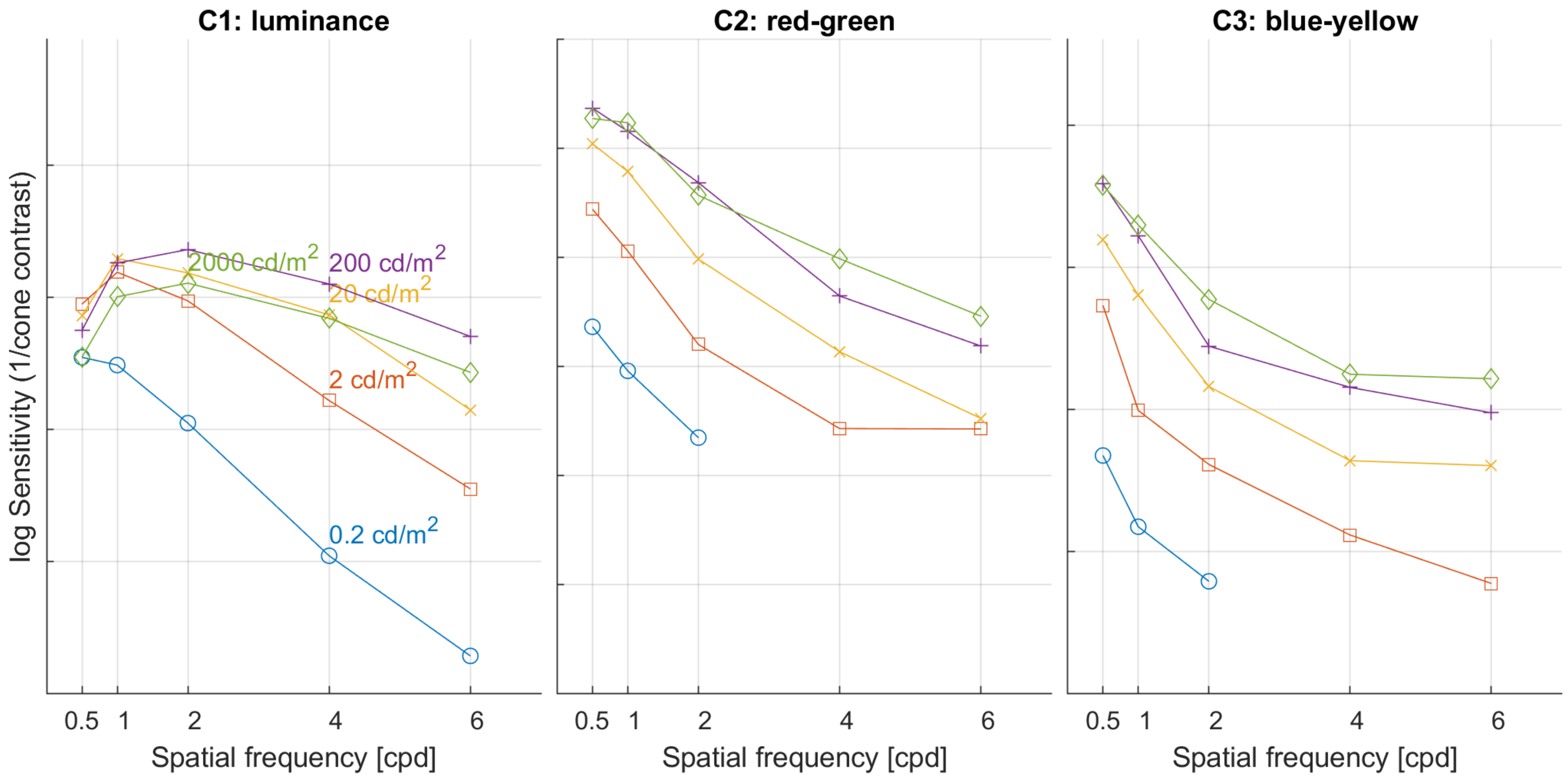
Color CSF across the luminance range



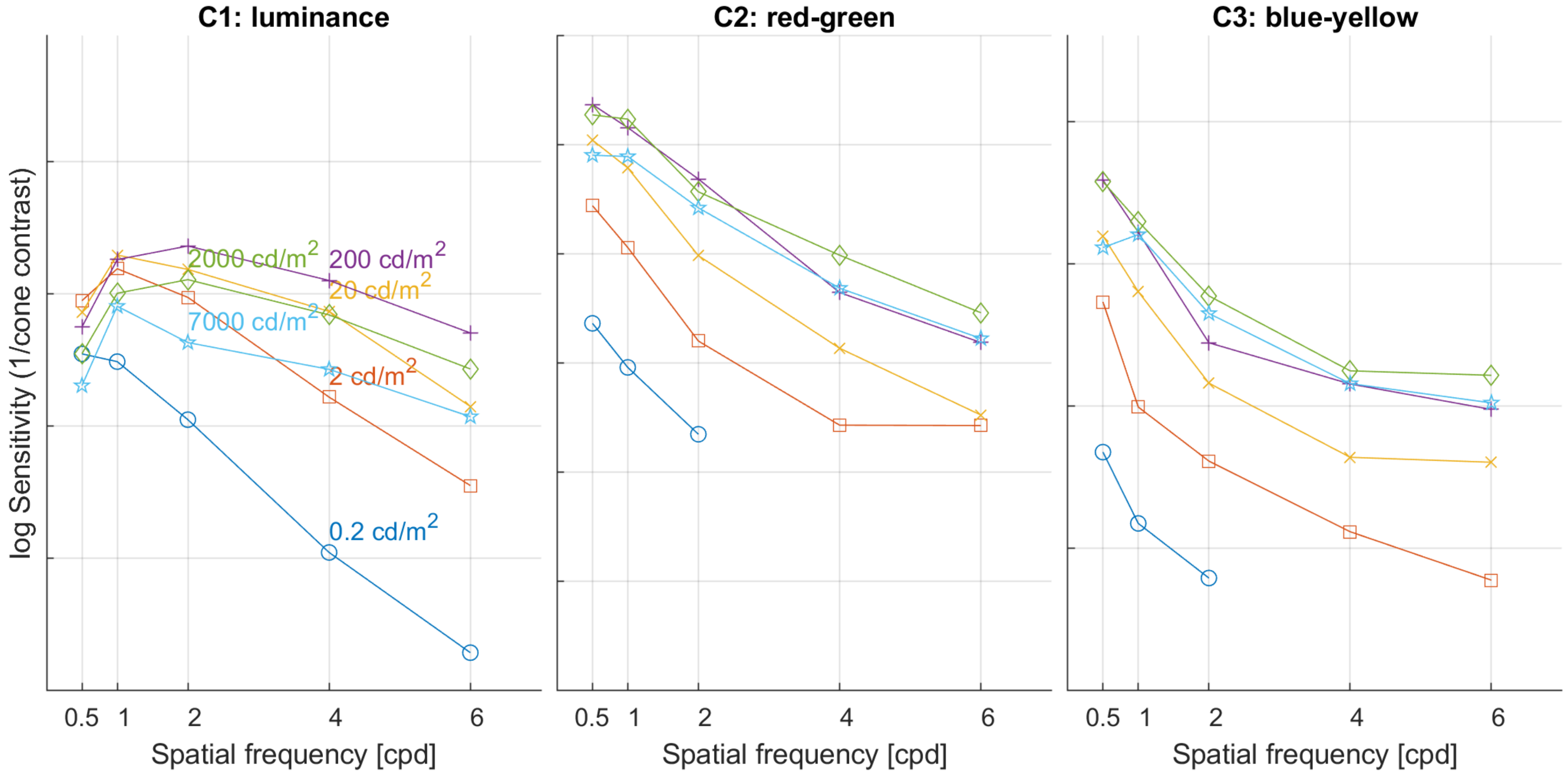
Color CSF across the luminance range



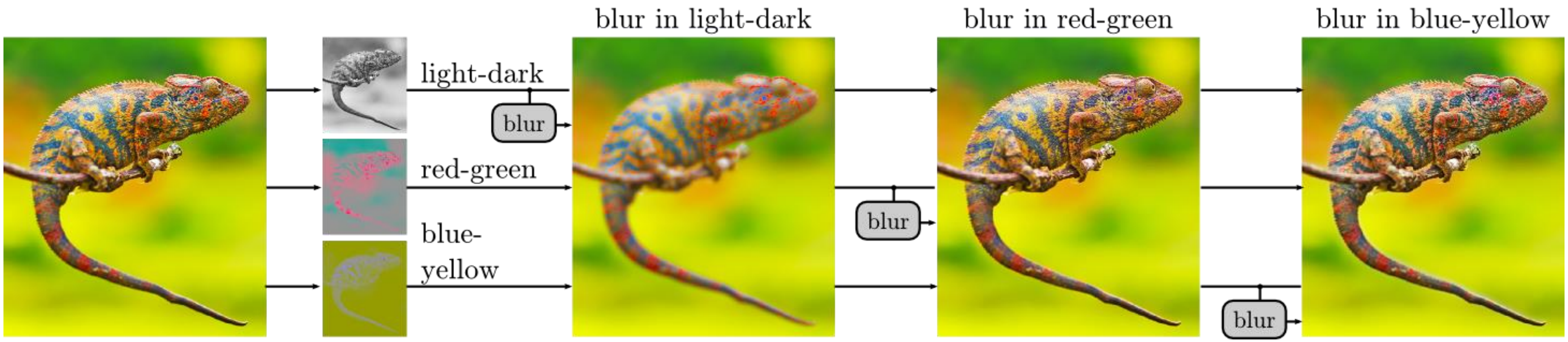
Color CSF across the luminance range



Color CSF across the luminance range



Visibility of blur

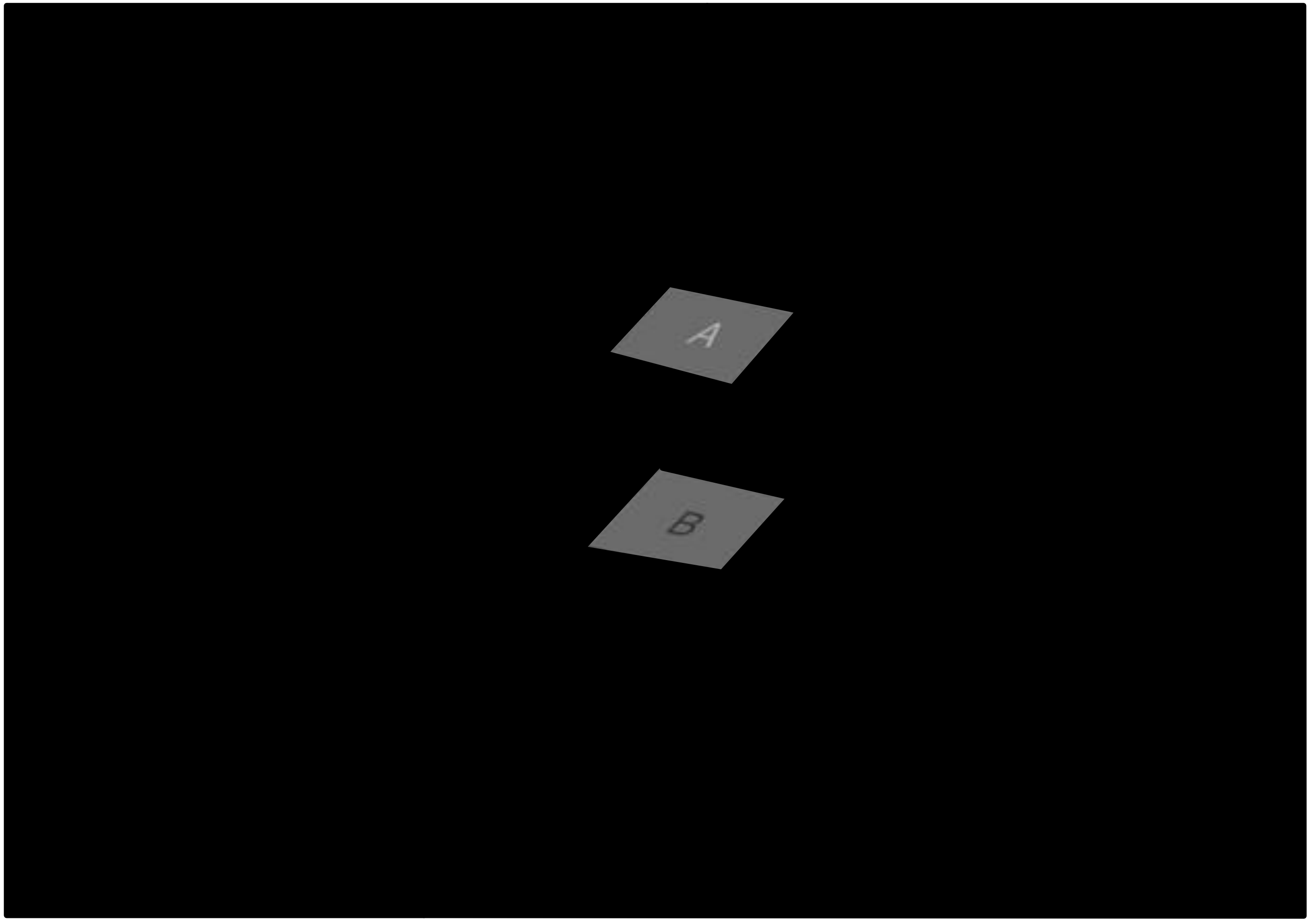


- The same amount of blur was introduced into light-dark, red-green and blue-yellow colour opponent channels
- The blur is only visible in light-dark channel
- This property is used in image and video compression
  - Sub-sampling of colour channels (4:2:1)

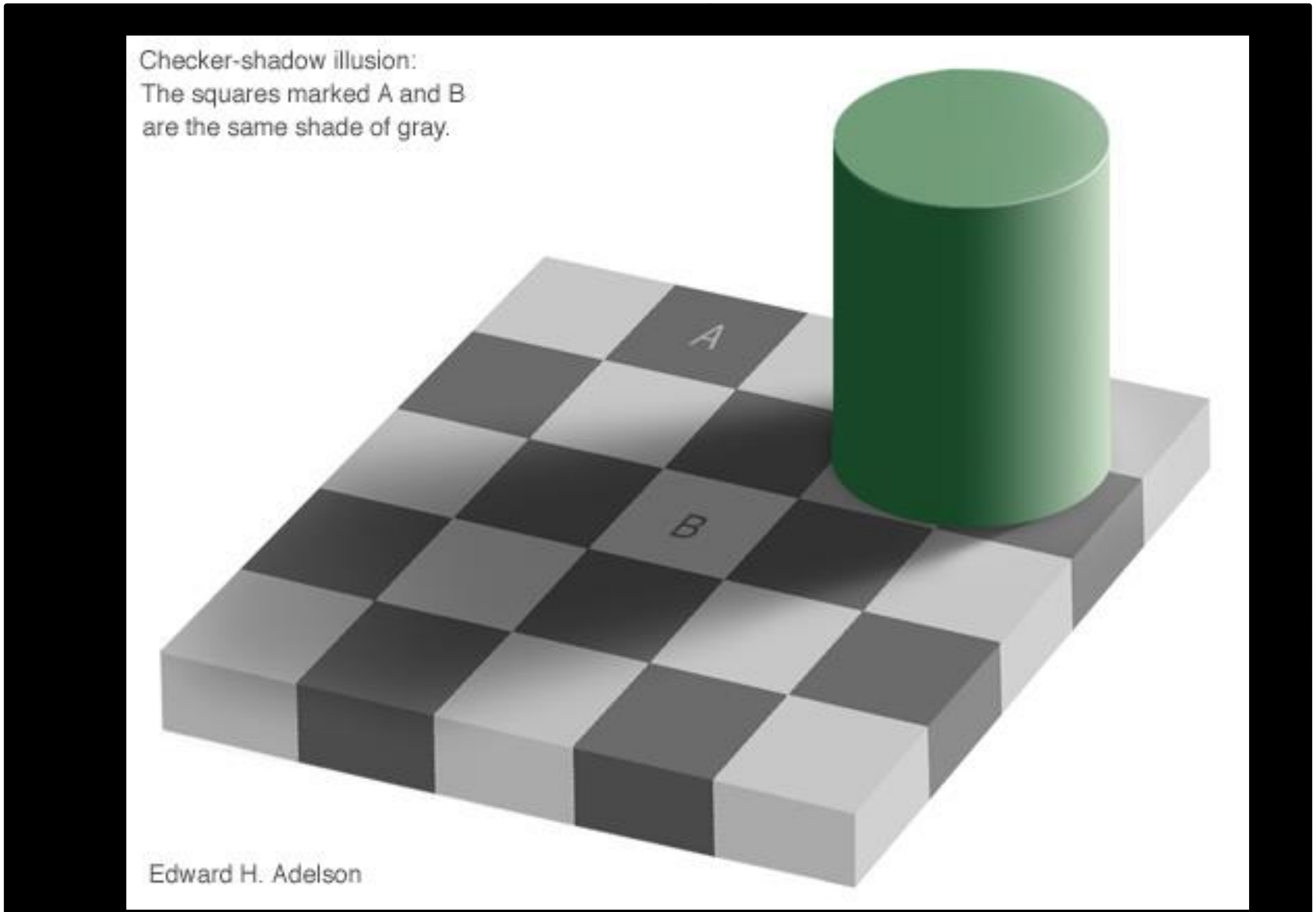
High(er) level vision

Simultaneous contrast

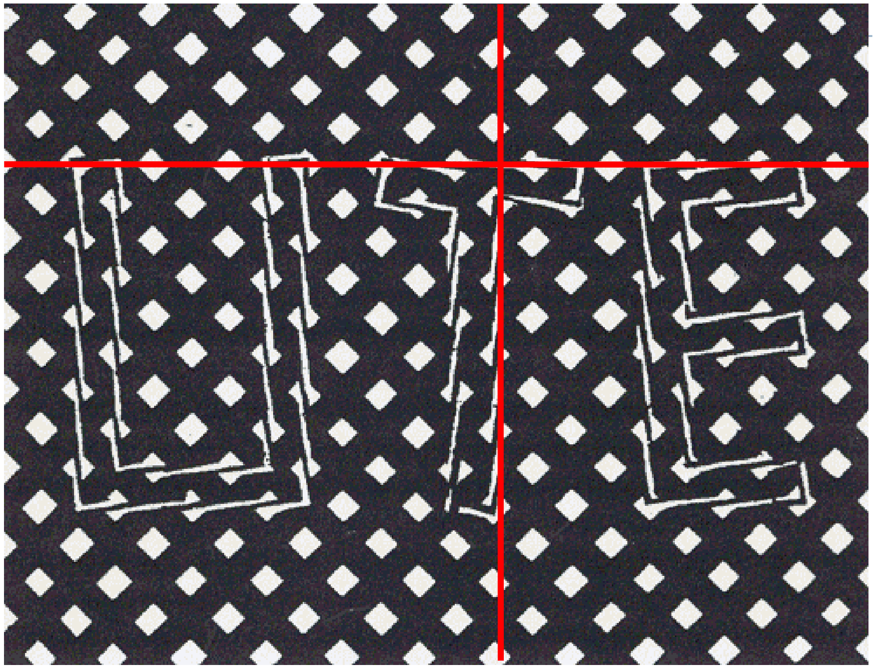
High-Level Contrast Processing

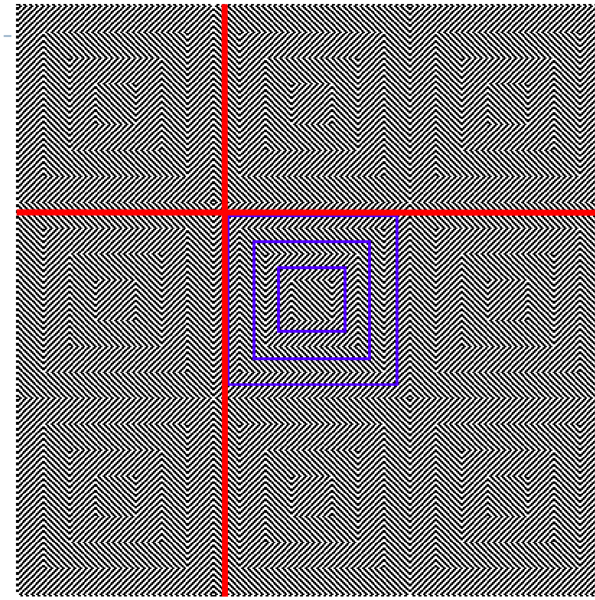


High-Level Contrast Processing

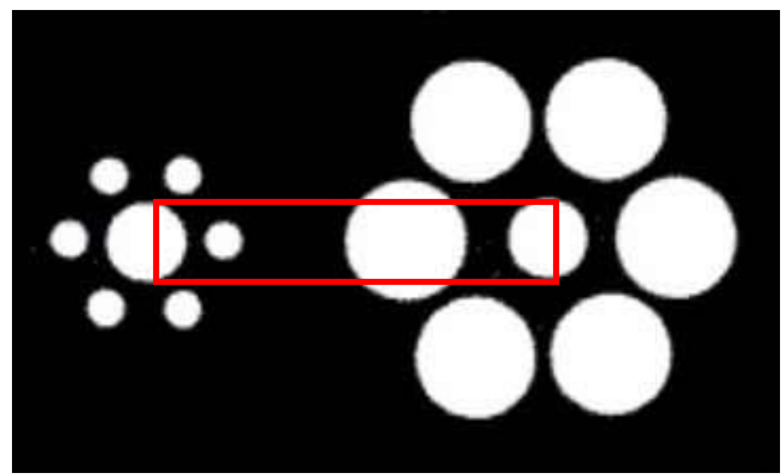


Shape Perception



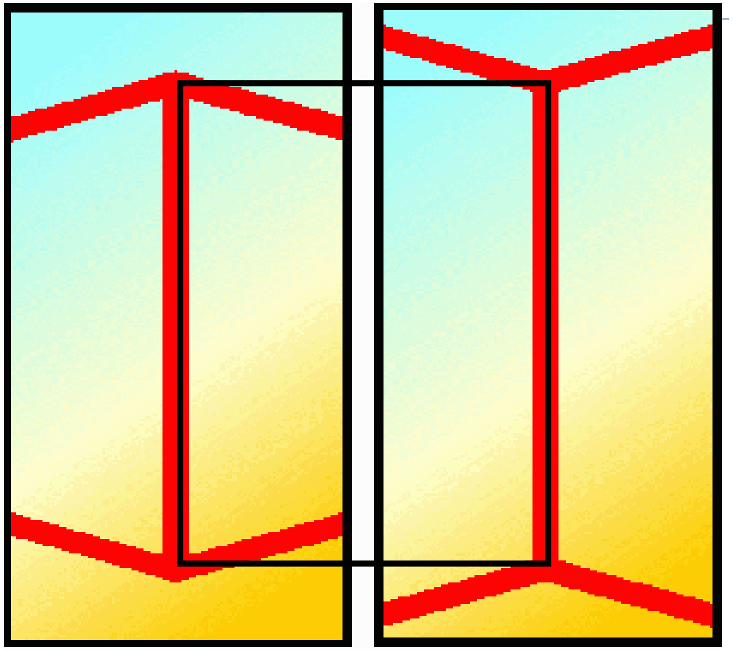


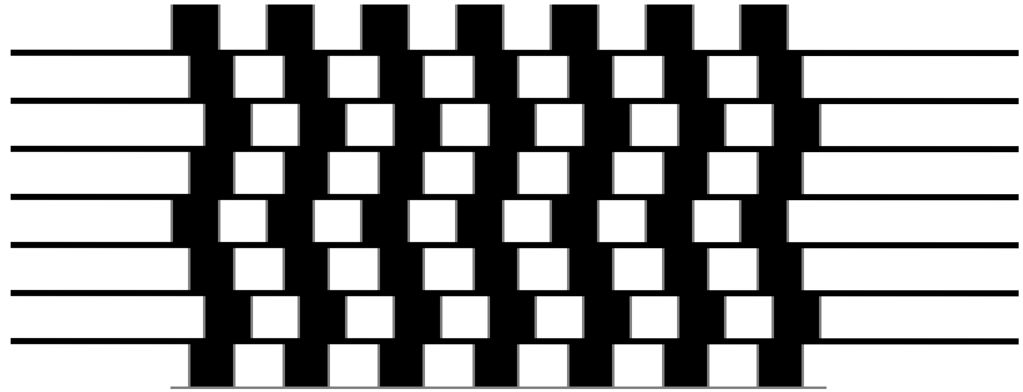
- Depends on surrounding primitives
  - Directional emphasis
  - Size emphasis



http://www.panoptikum.net/optischetaeuschungen/index.html

Shape Processing: Geometrical Clues



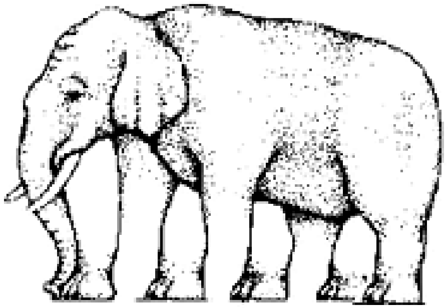


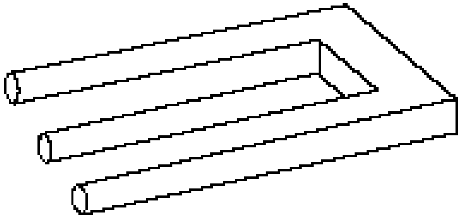
http://www.panoptikum.net/optischetaeuschungen/index.html

- Automatic geometrical interpretation
  - 3D perspective
  - Implicit scene depth

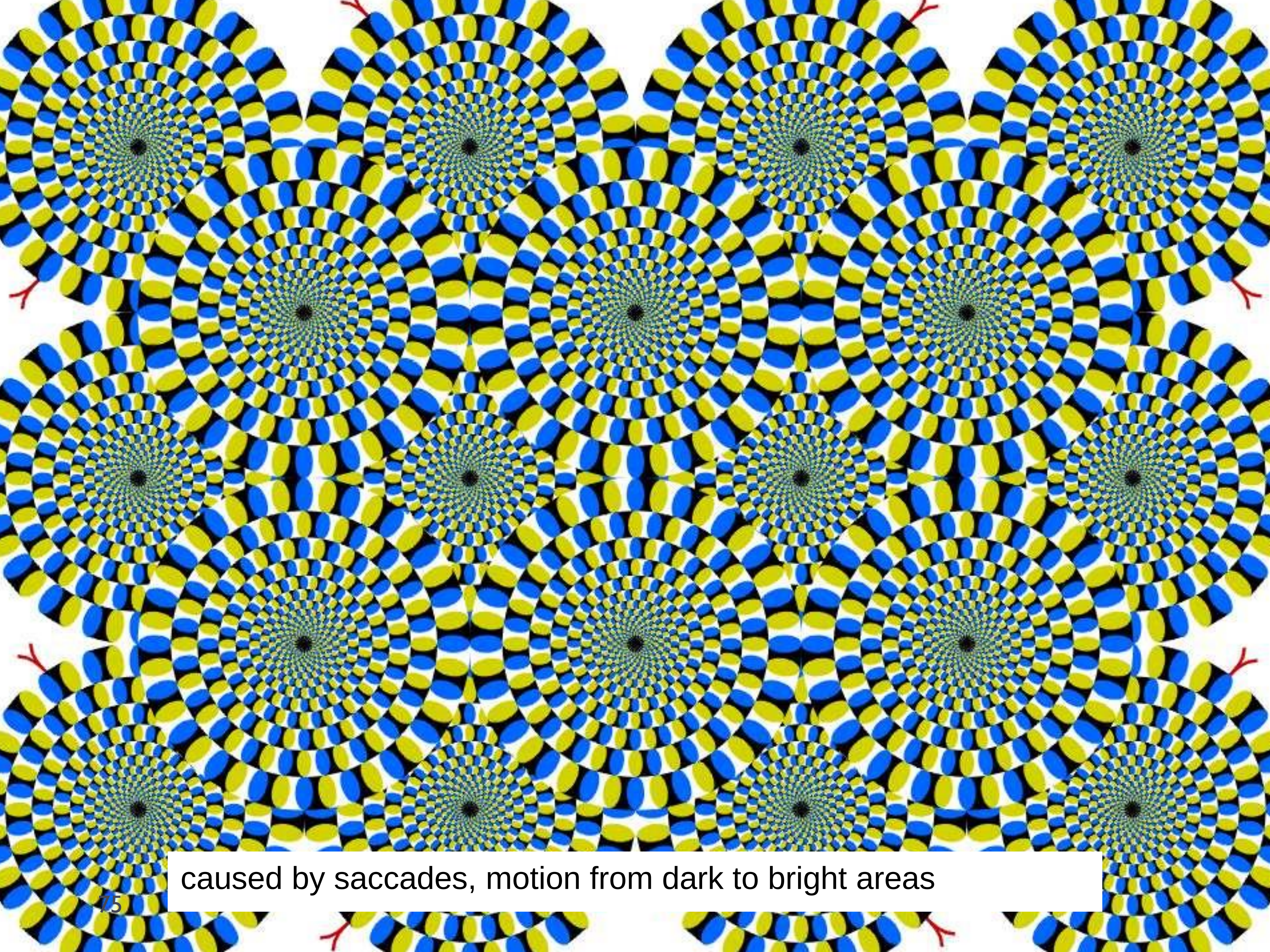
Impossible Scenes

- Escher et.al.
  - Confuse HVS by presenting contradicting visual clues
  - Local vs. global processing





http://www.panoptikum.net/optischetaeuschungen/index.html



caused by saccades, motion from dark to bright areas

Law of closure

References

- Wandell, B. A. (1995). *Foundations of vision*. Sinauer Associates.
- Mantiuk, R. K., Myszkowski, K., & Seidel, H. (2015). High Dynamic Range Imaging. In *Wiley Encyclopedia of Electrical and Electronics Engineering*. Wiley.
  - Section 2.4
  - Available online: http://www.cl.cam.ac.uk/~rkm38/hdri_book.html