



Advanced Graphics and Image Processing

Models of early visual perception

Part 1/6 – perceived brightness of light

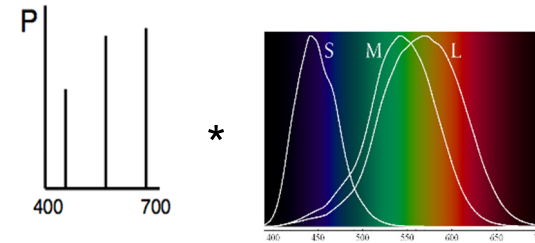
Rafal Mantiuk

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Many graphics/display solutions are motivated by visual perception



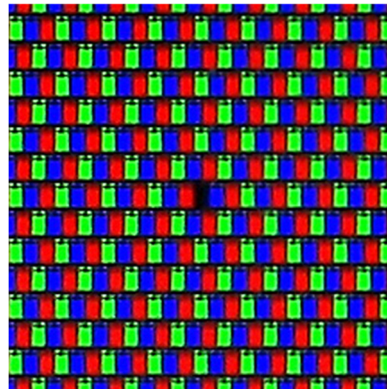
Image & video compression



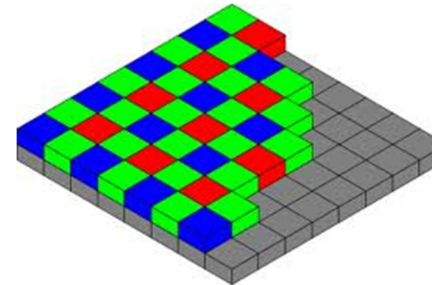
Display spectral emission - metamerism



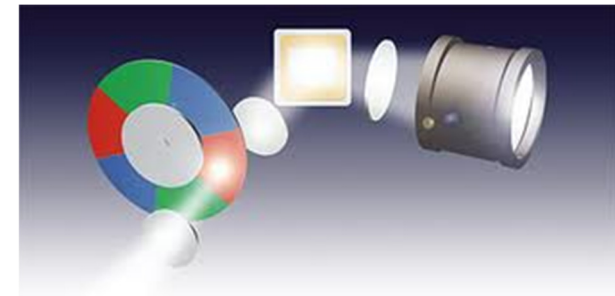
Halftoning



Display's subpixels



Camera's Bayer pattern



Color wheel in DLPs

Luminance (again)

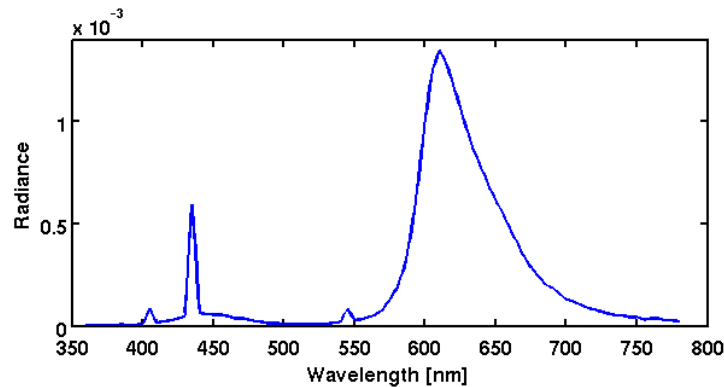
- Luminance – measure of light weighted by the response of the achromatic mechanism. Units: cd/m^2

Luminance

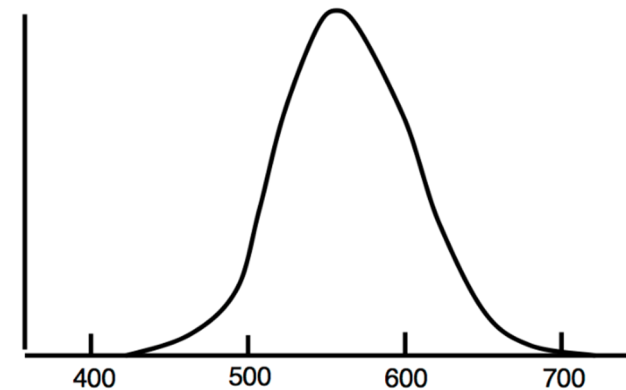
$$L_V = \int_{350}^{700} kL(\lambda)V(\lambda)d\lambda$$

$$k = \frac{1}{683.002}$$

Light spectrum (radiance)

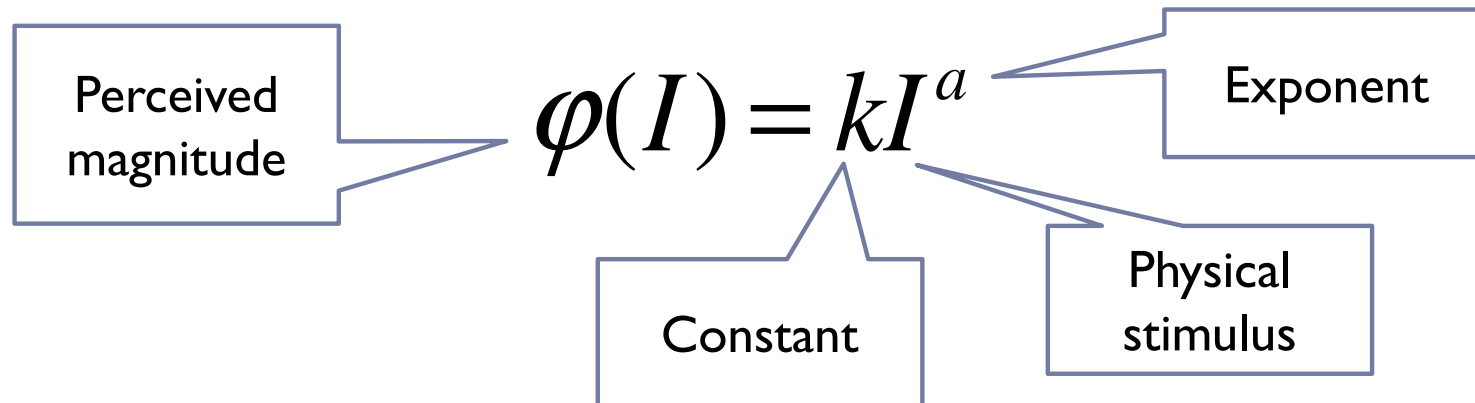


Luminous efficiency function (weighting)



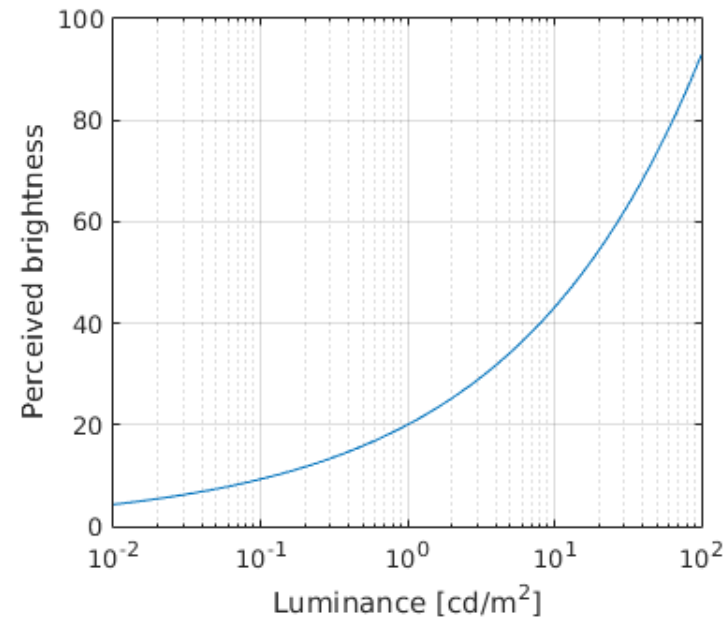
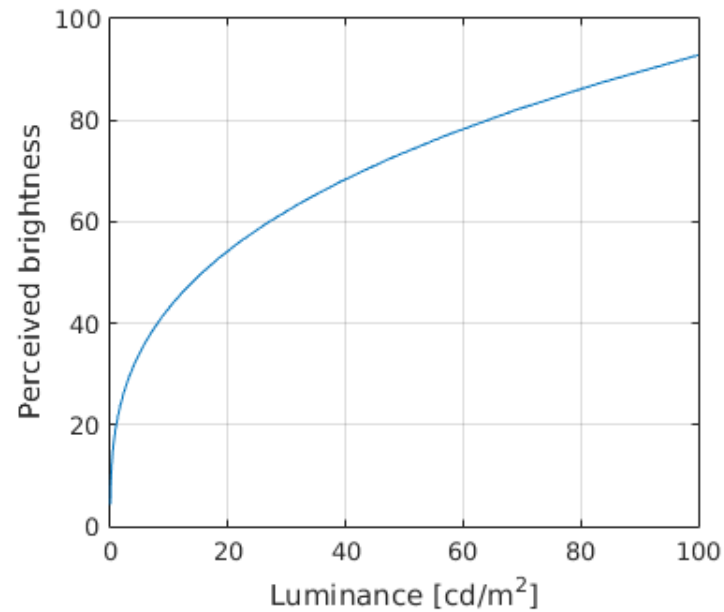
Steven's power law for brightness

- ▶ 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:



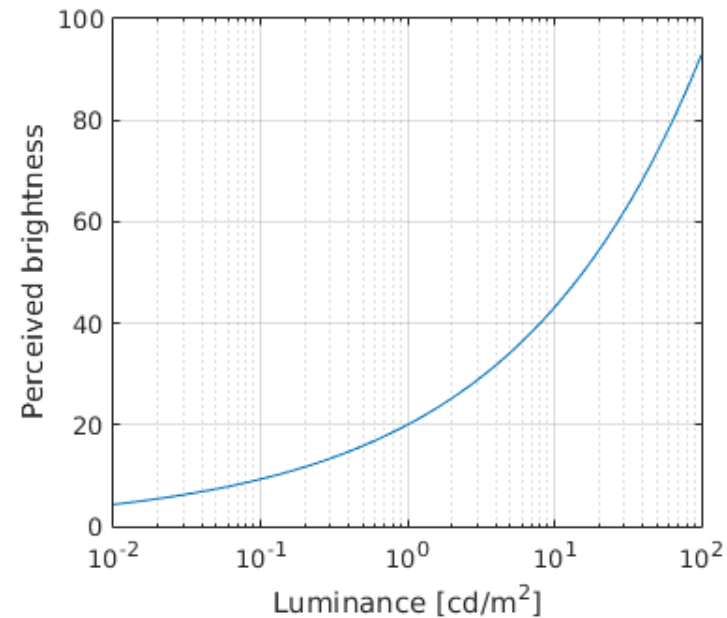
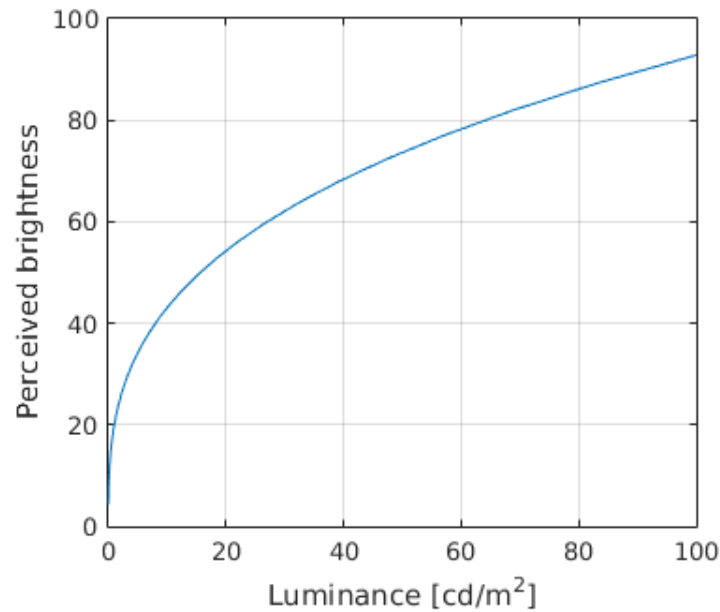
- ▶ For brightness (5 deg target in dark), $a = 0.3$

Steven's law for brightness

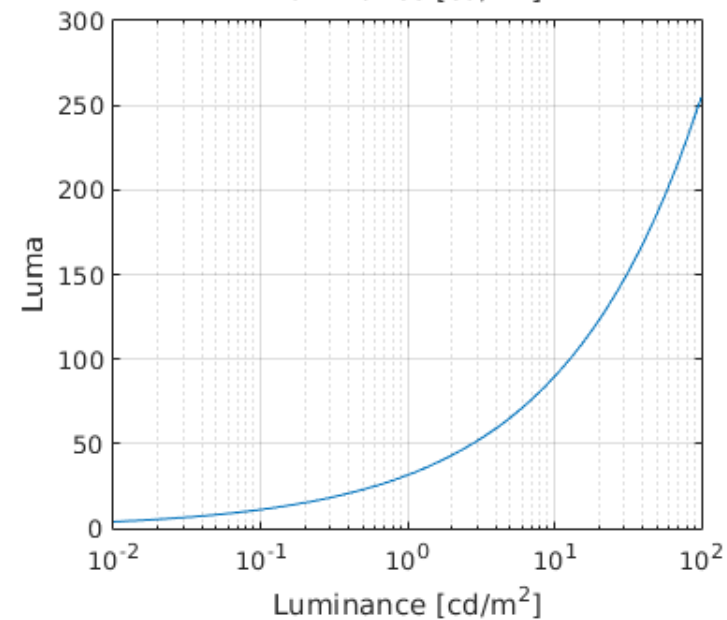
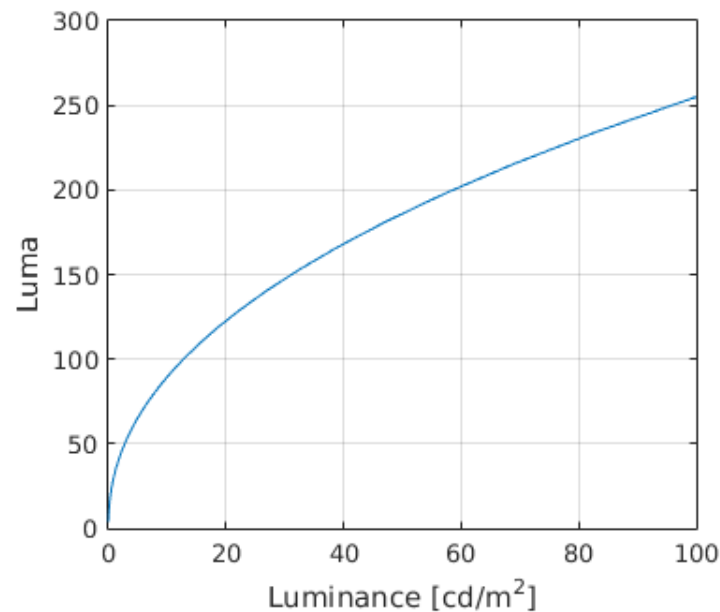


Steven's law vs. Gamma correction

Stevens' law
 $a=0.3$



Gamma function
Gamma = 2.2





Advanced Graphics and Image Processing

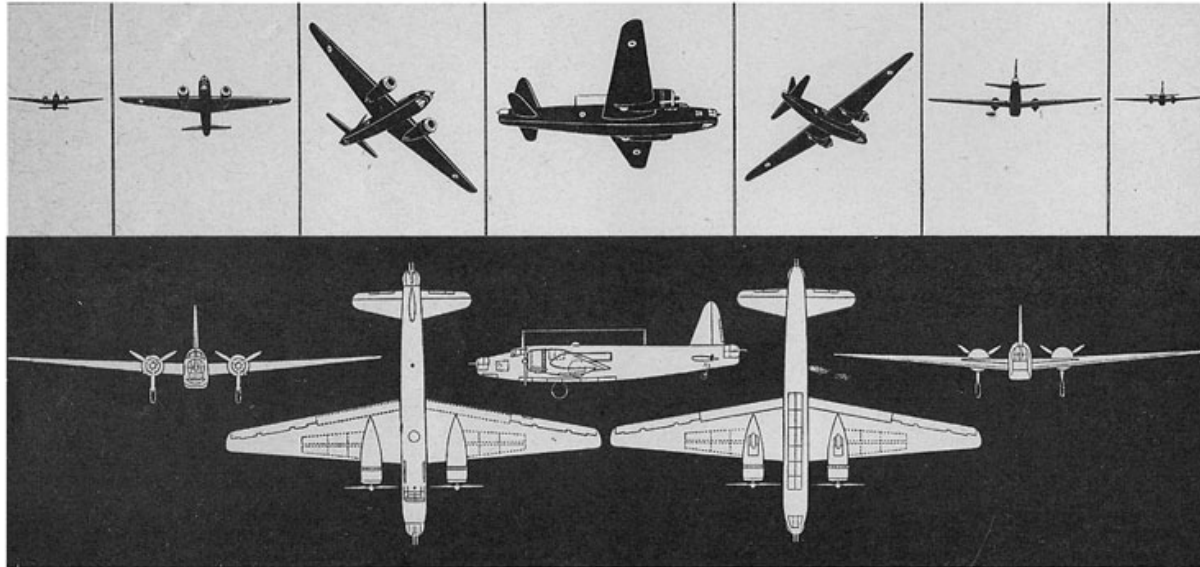
Models of early visual perception

Part 2/6 – contrast detection

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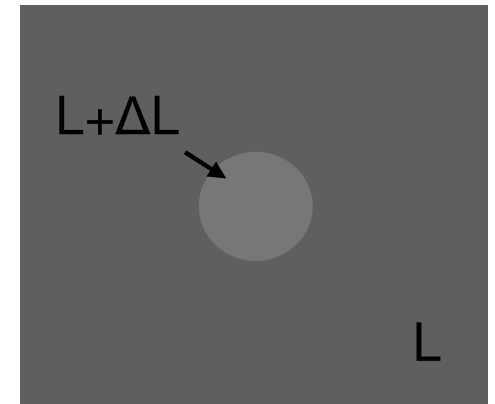
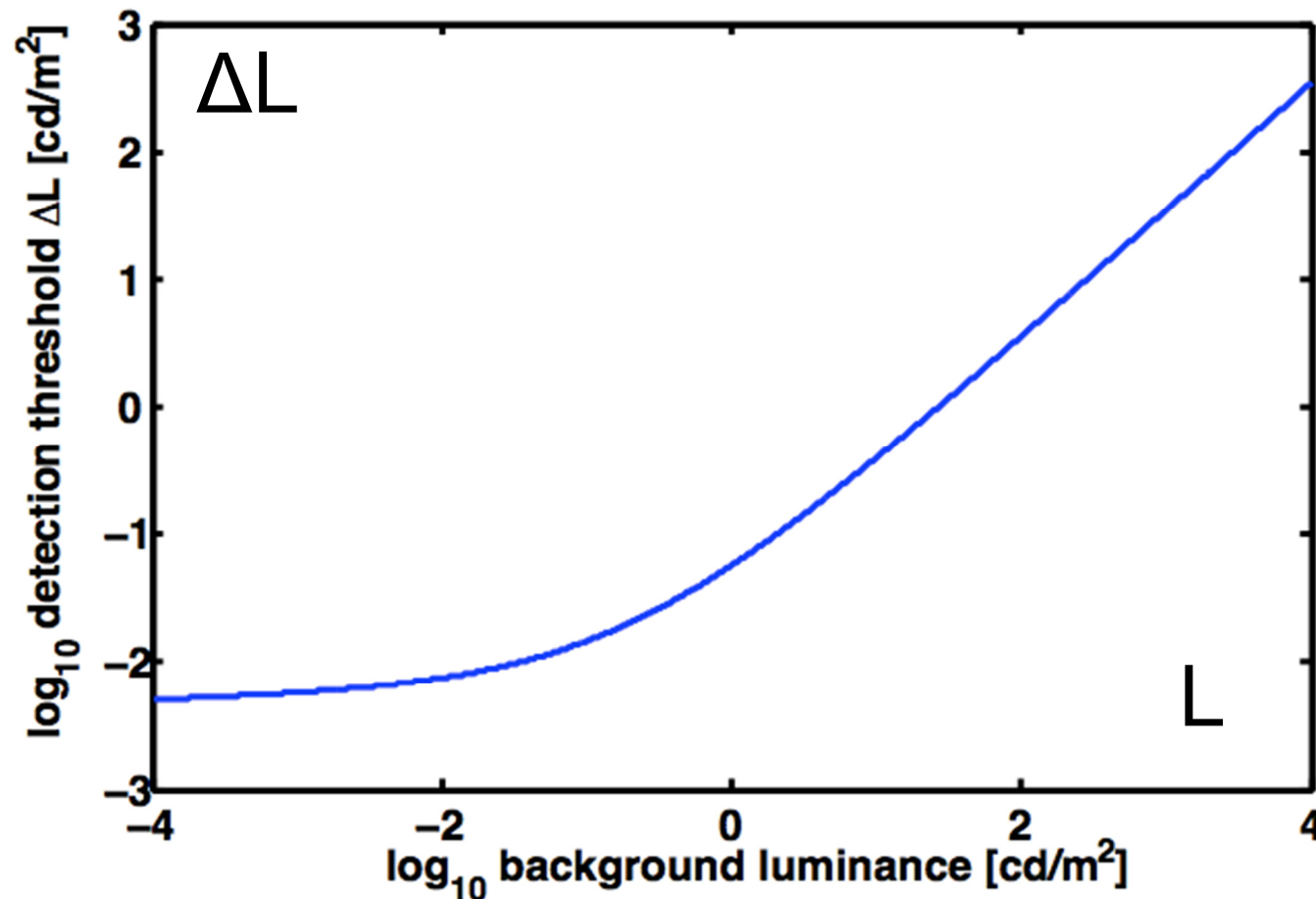
Detection thresholds



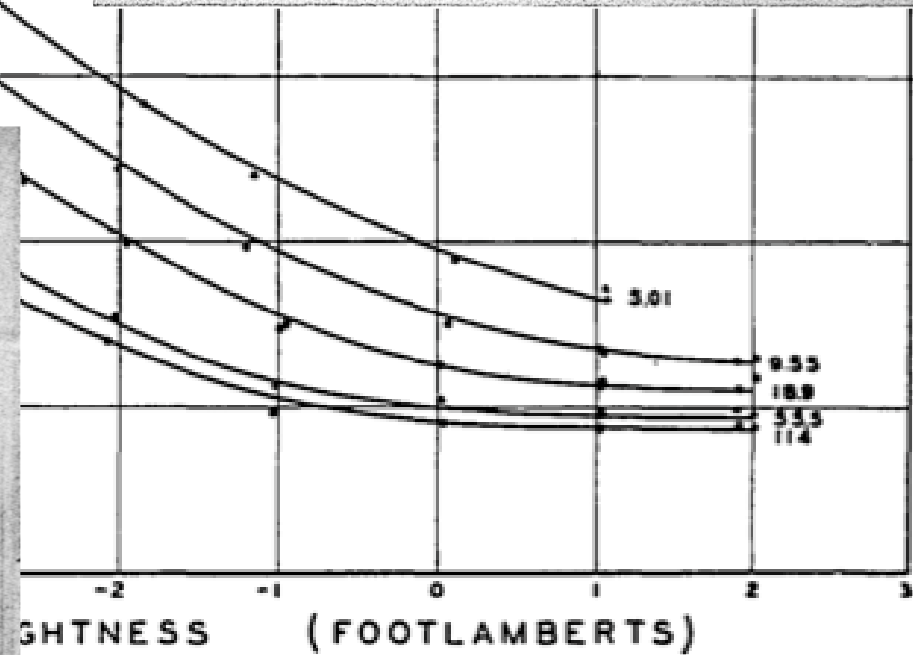
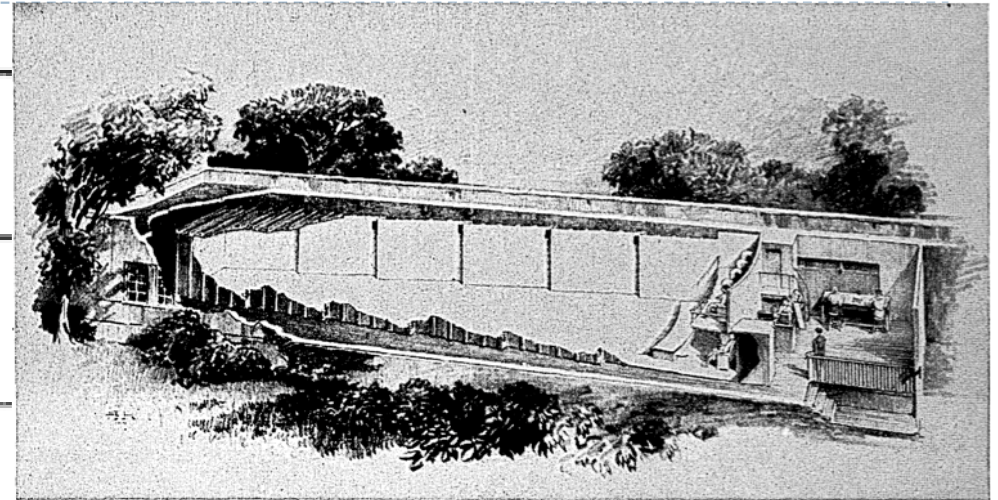
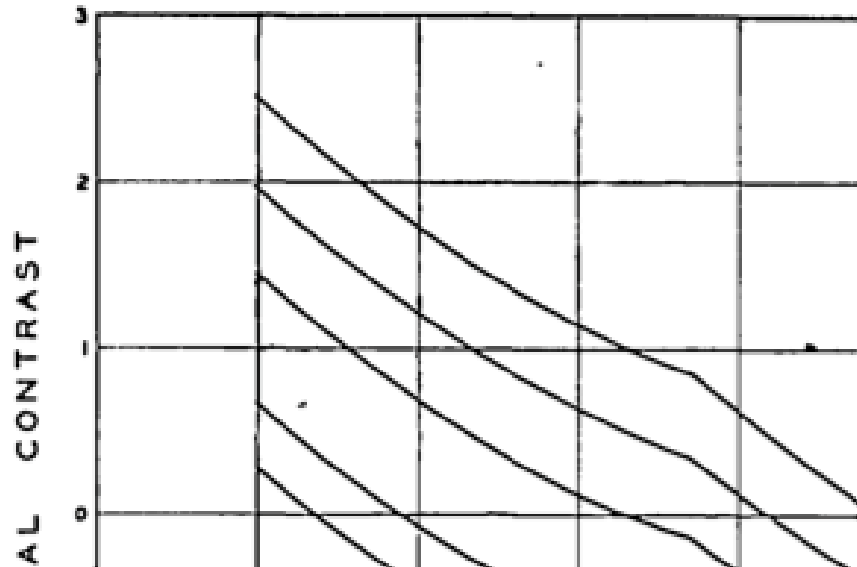
- ▶ The smallest detectable difference between
 - ▶ the luminance of the object and
 - ▶ the luminance of the background

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

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

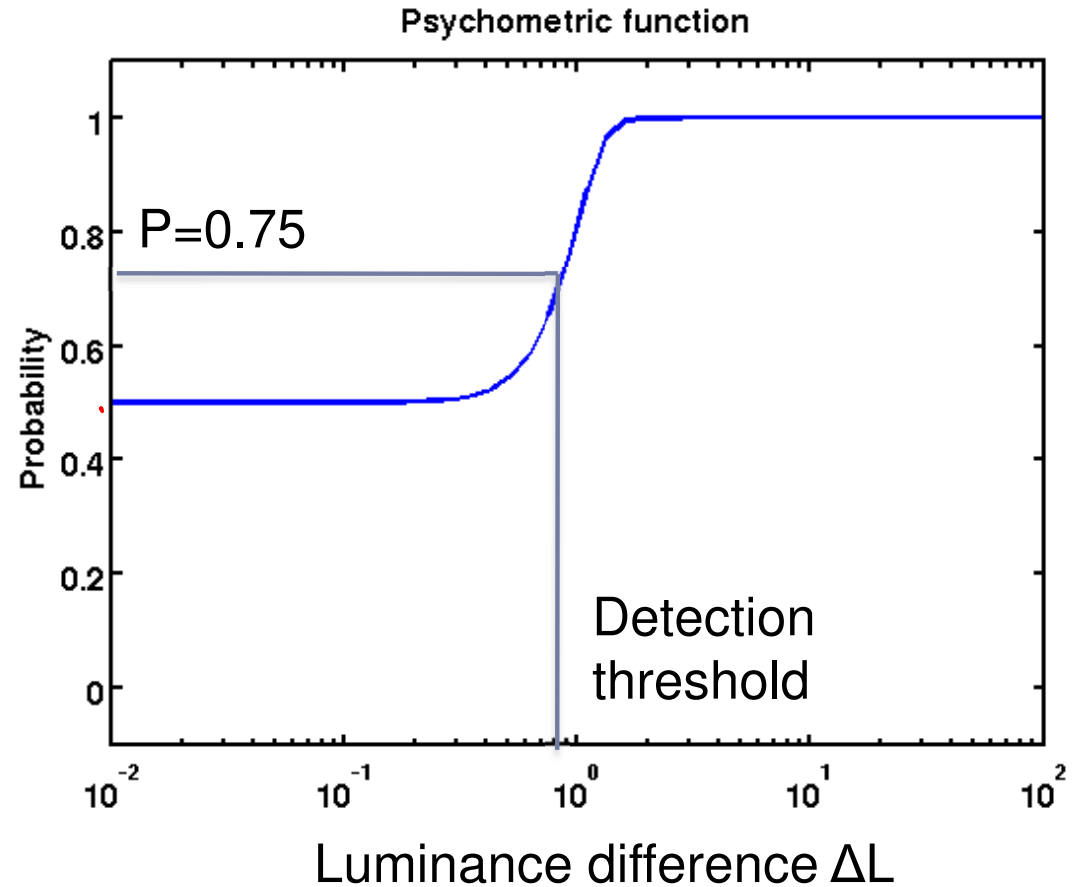
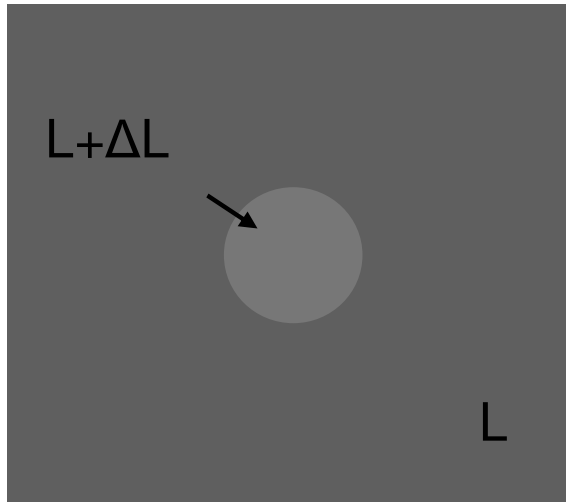


t.v.i. measurements – Blackwell 1946



Psychophysics

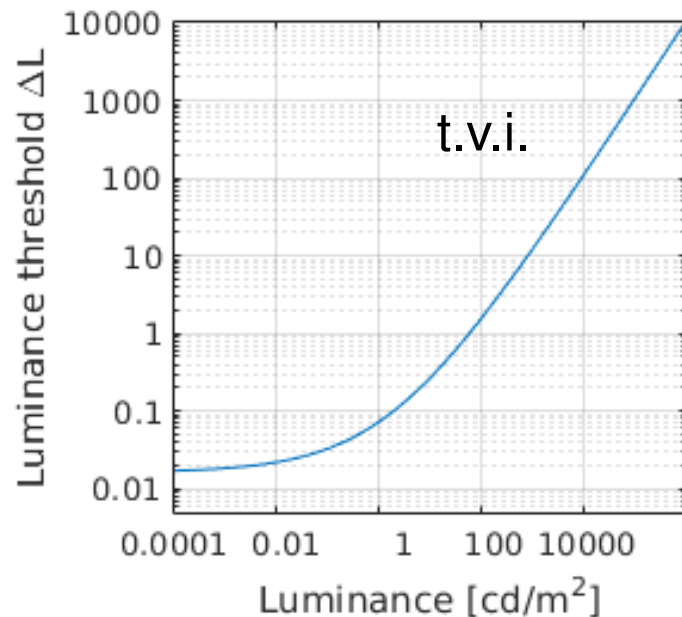
Threshold experiments



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

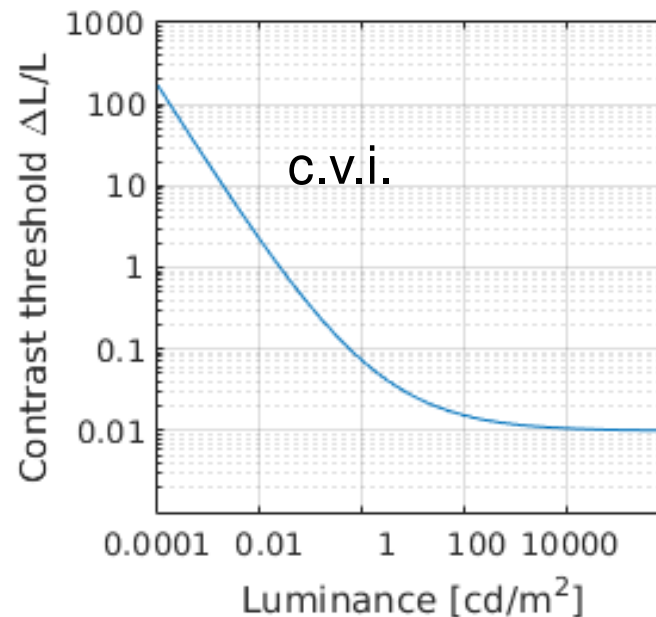
- The same data, different representation

Threshold vs. intensity



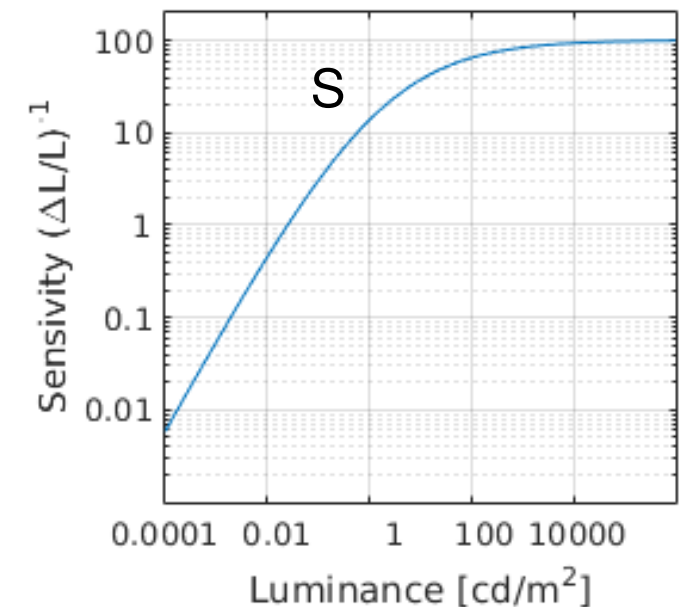
$$\Delta L = L_{disk} - L_{background}$$

Contrast vs. intensity



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

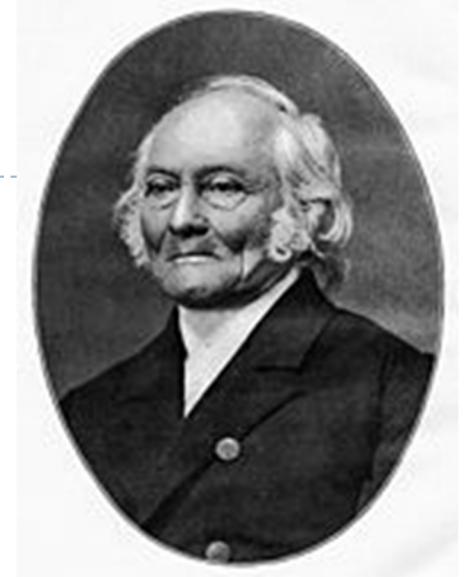
Sensitivity



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

Sensitivity to luminance

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



Ernst Heinrich Weber
[From wikipedia]

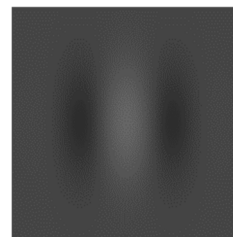
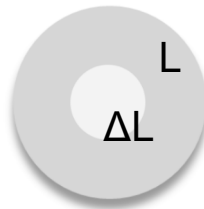
The smallest
detectable
luminance
difference

Background
(adapting)
luminance

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

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

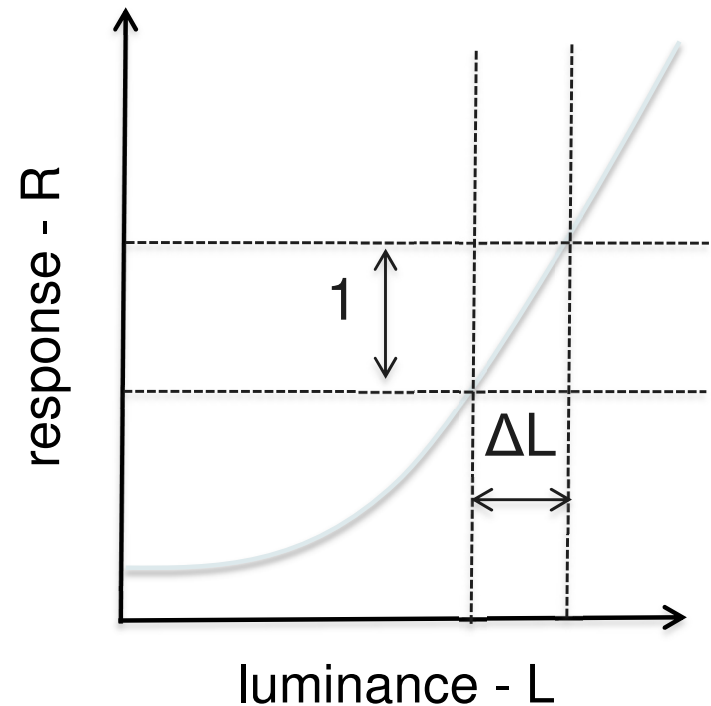
$$\frac{dR}{dl}(L) = \frac{1}{\Delta L(L)}$$

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

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

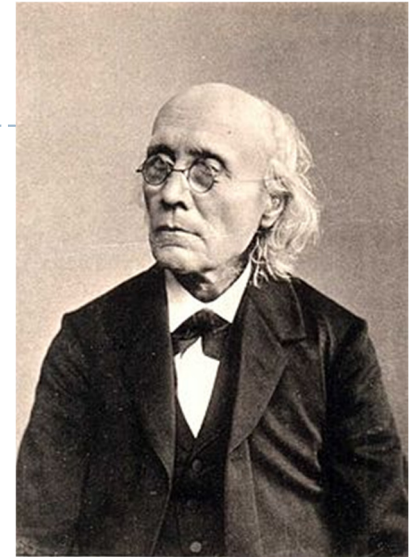
- ▶ the response of the visual system to light is:

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

Fechner law

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

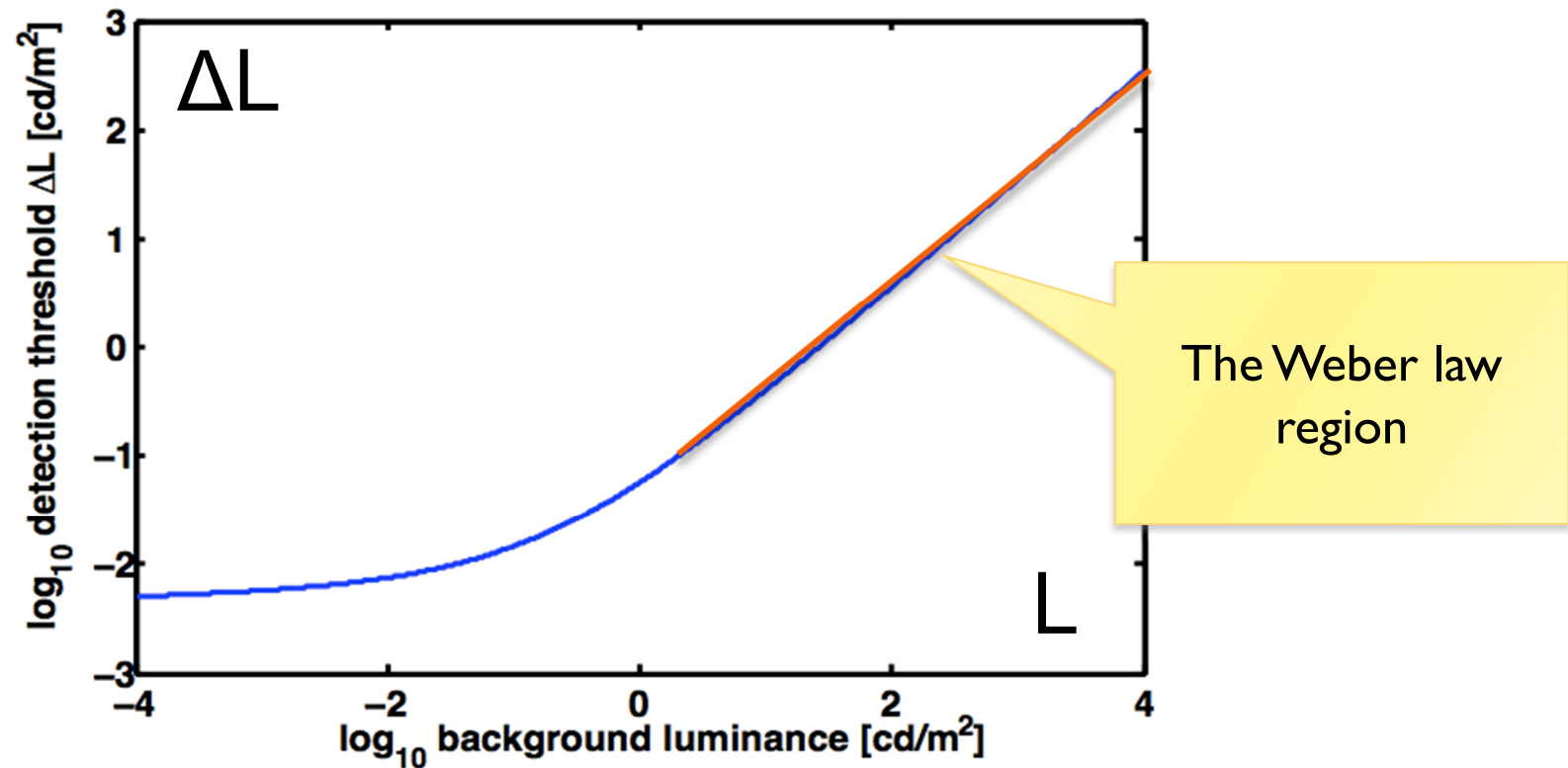
- ▶ Response of the visual system to luminance is **approximately** logarithmic



Gustav Fechner
[From Wikipedia]

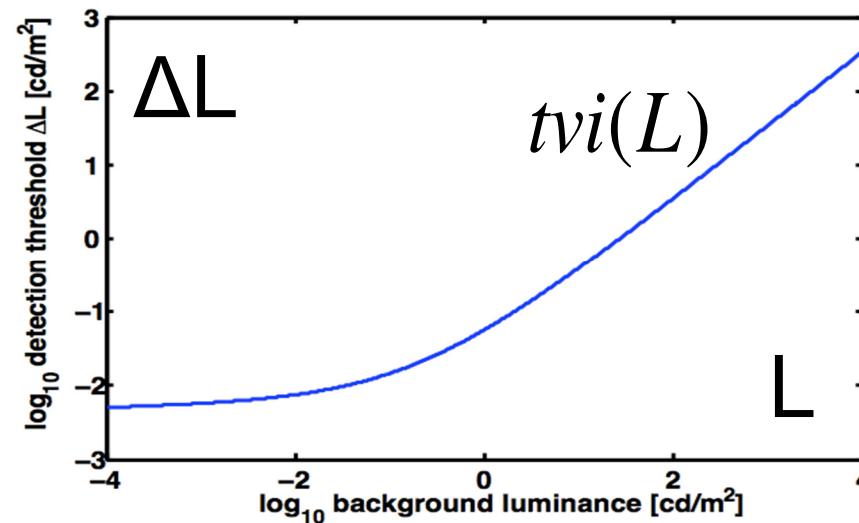
But...the Fechner law does not hold for the full luminance range

- ▶ 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:



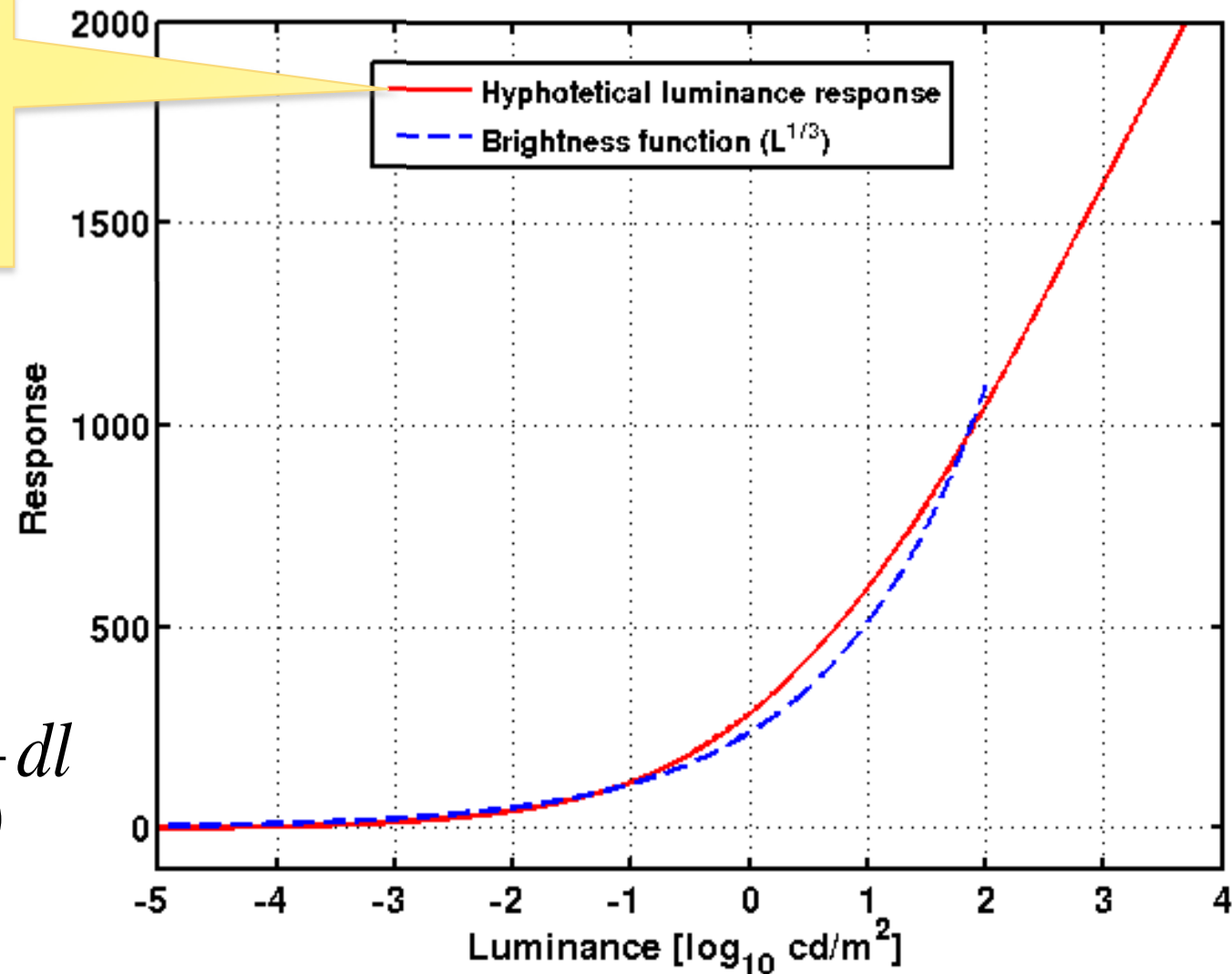
- ▶ we can get a more accurate estimate of the “response”:

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

Fechnerian integration and Stevens' law

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

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

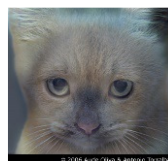
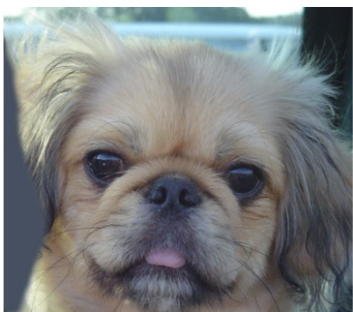


Applications of JND encoding – R(L)

- ▶ **DICOM grayscale function**
 - ▶ Function used to encode signal for medical 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



The Future of Vision





Advanced Graphics and Image Processing

Models of early visual perception

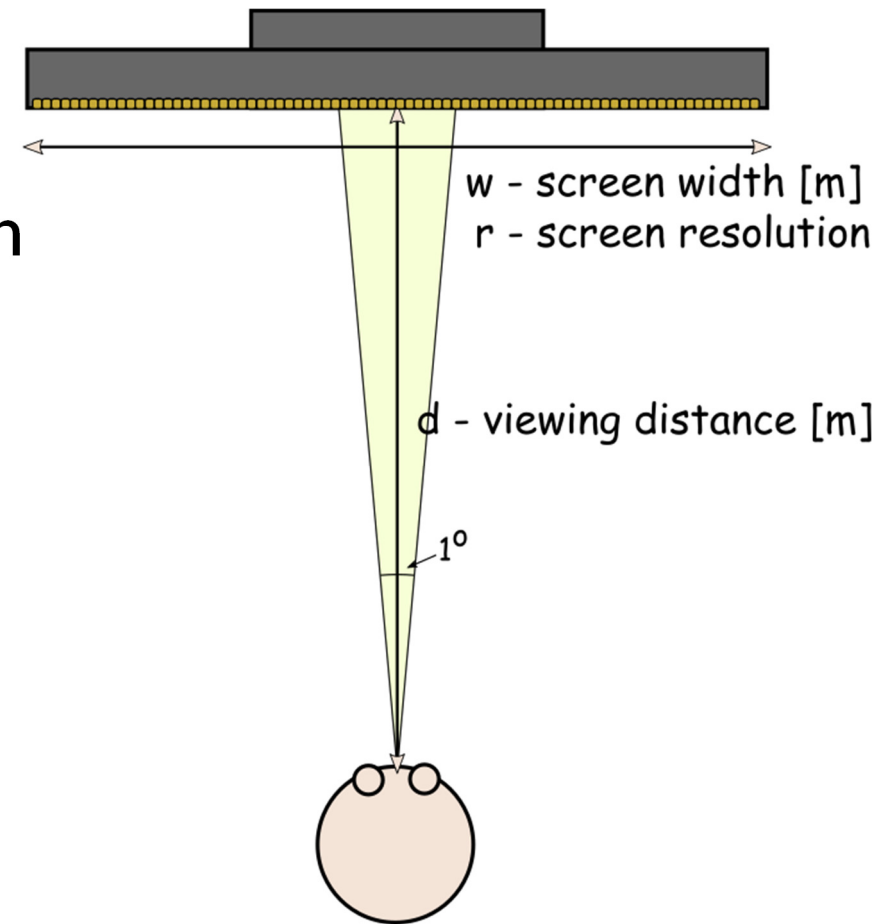
Part 3/6 – spatial contrast sensitivity and contrast constancy

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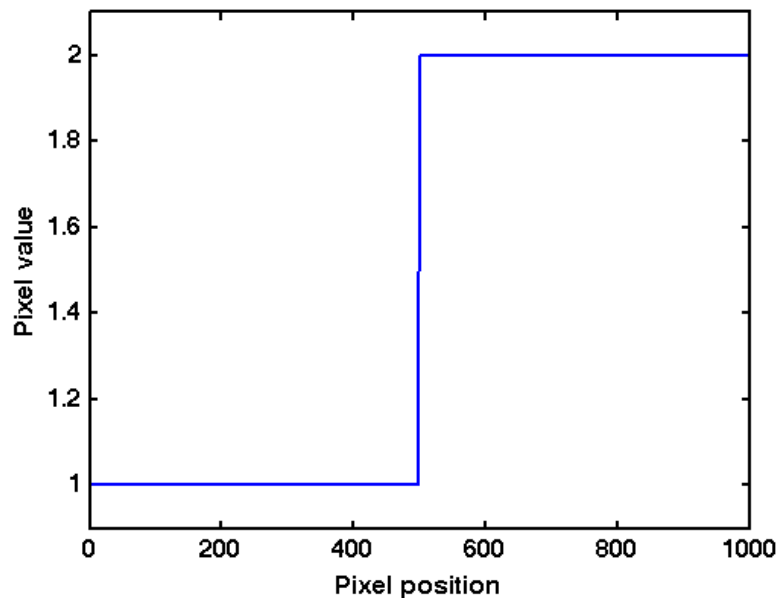
Resolution and sampling rate

- ▶ 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]

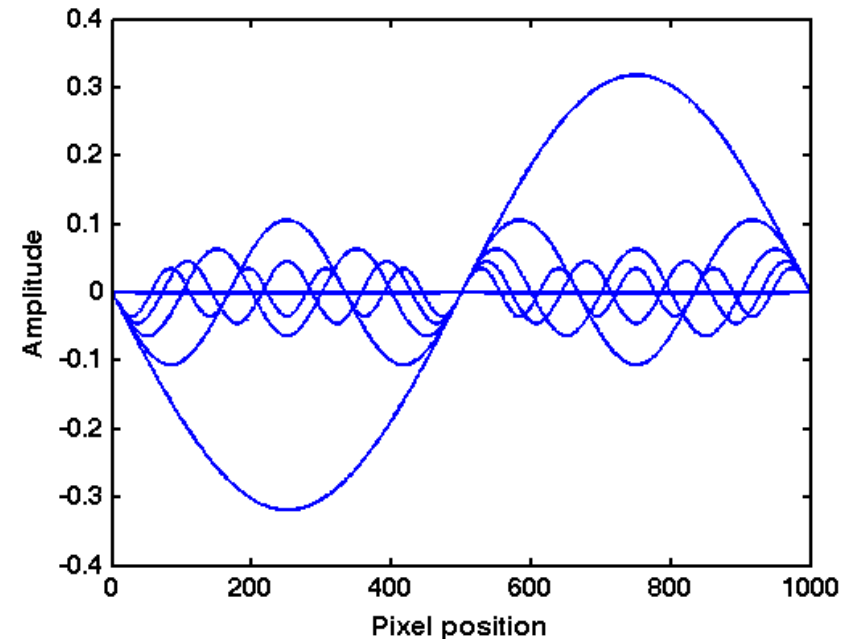


Fourier analysis

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



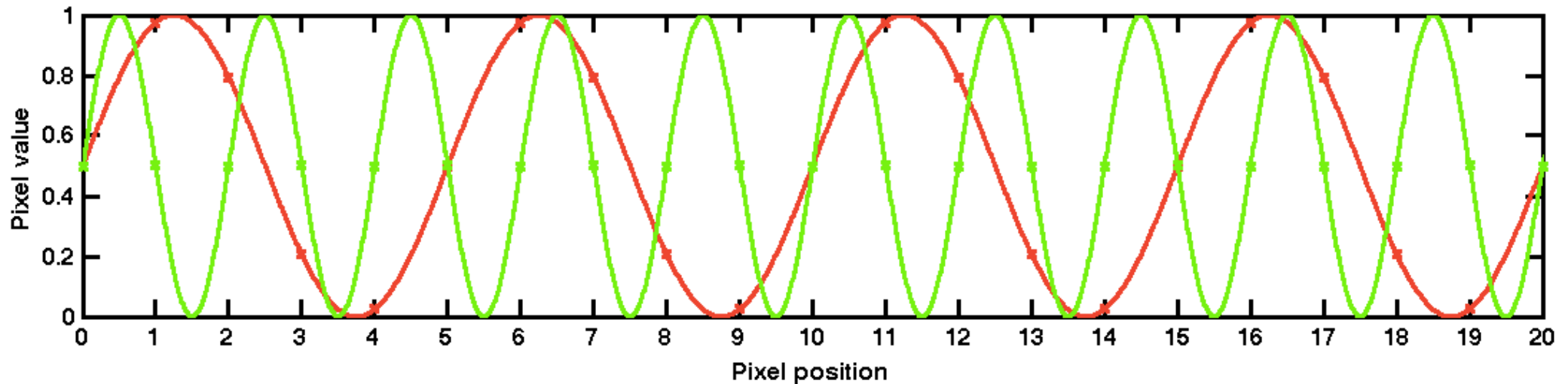
$$= \sum$$



- ▶ Think of “equalizer” in audio software, which manipulates each frequency

Spatial frequency in images

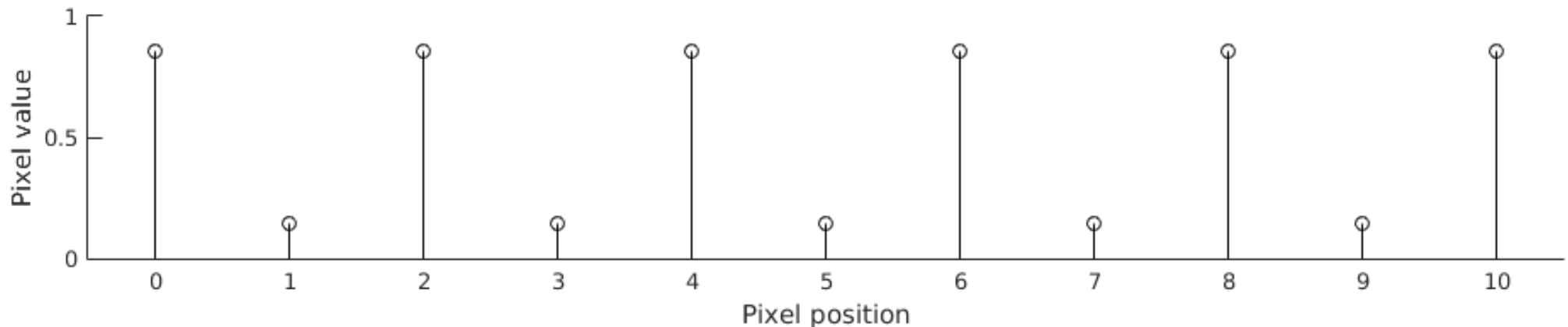
- ▶ Image space units: cycles per sample (or cycles per pixel)



- ▶ 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

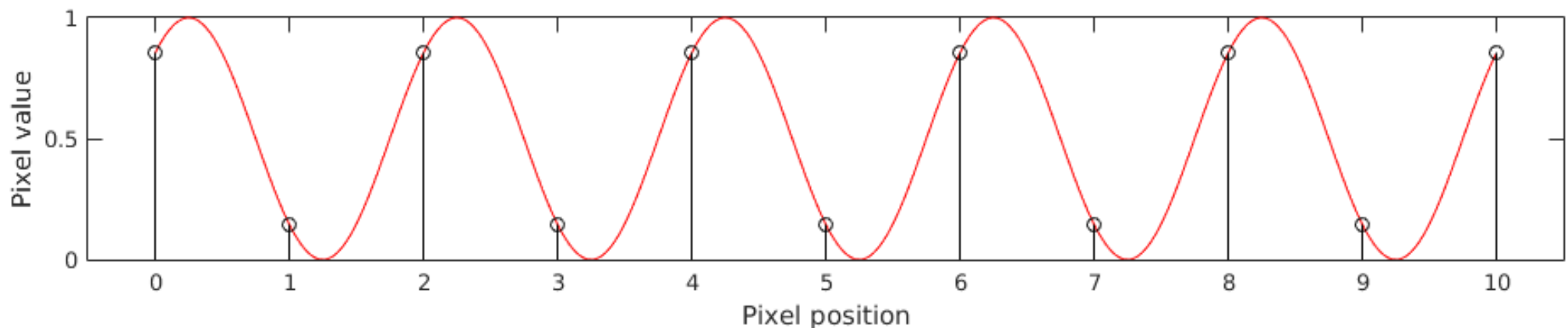
- ▶ Sampling density restricts the highest spatial frequency signal that can be (uniquely) reconstructed
 - ▶ Sampling density – how many pixels per image/visual angle/...



- ▶ 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

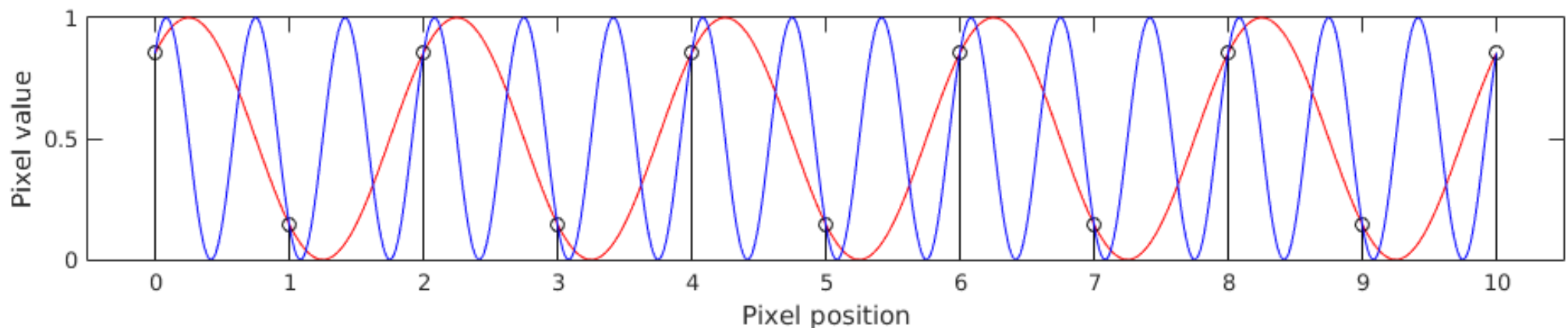
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Nyquist frequency

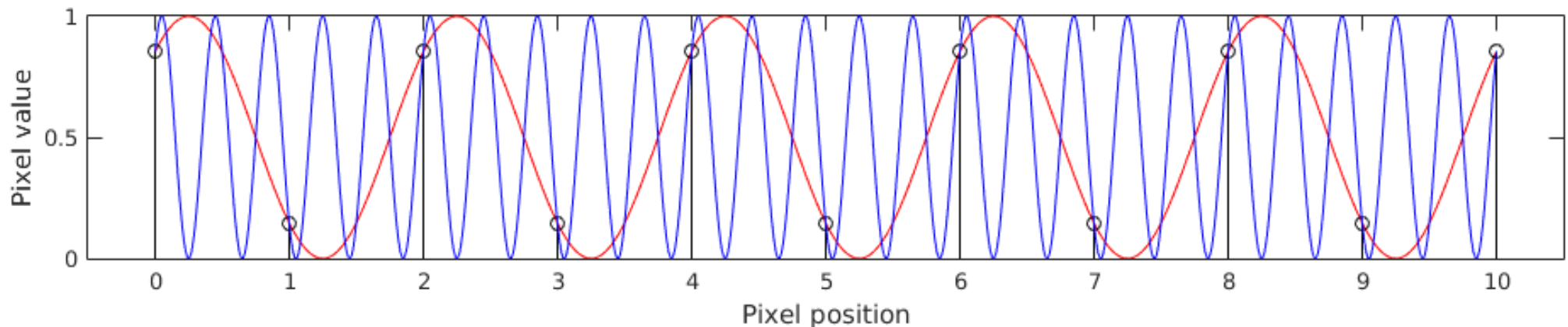
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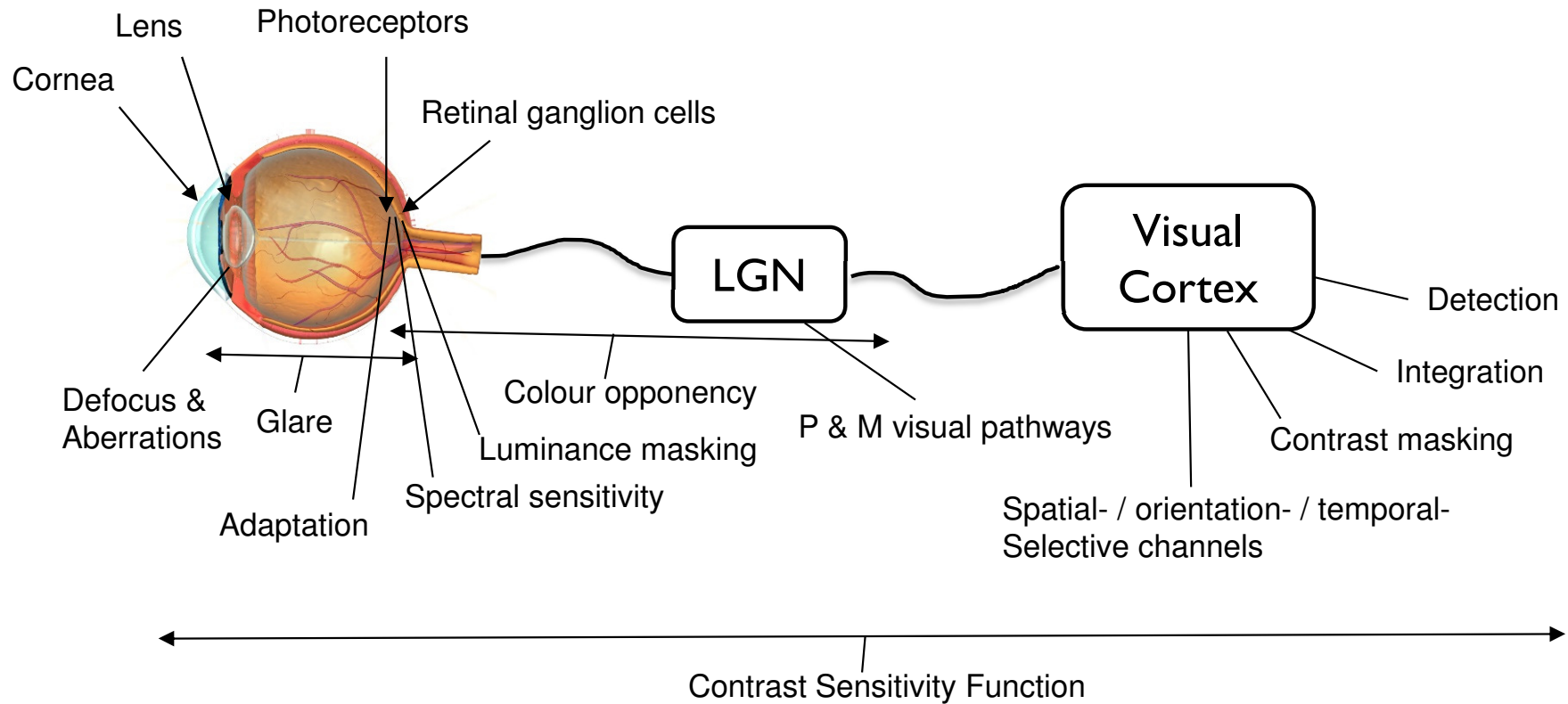


- ▶ Any number of sinusoids can be fitted to this set of samples
- ▶ It is possible to fit an infinite number of sinusoids if we allow infinitely high frequency

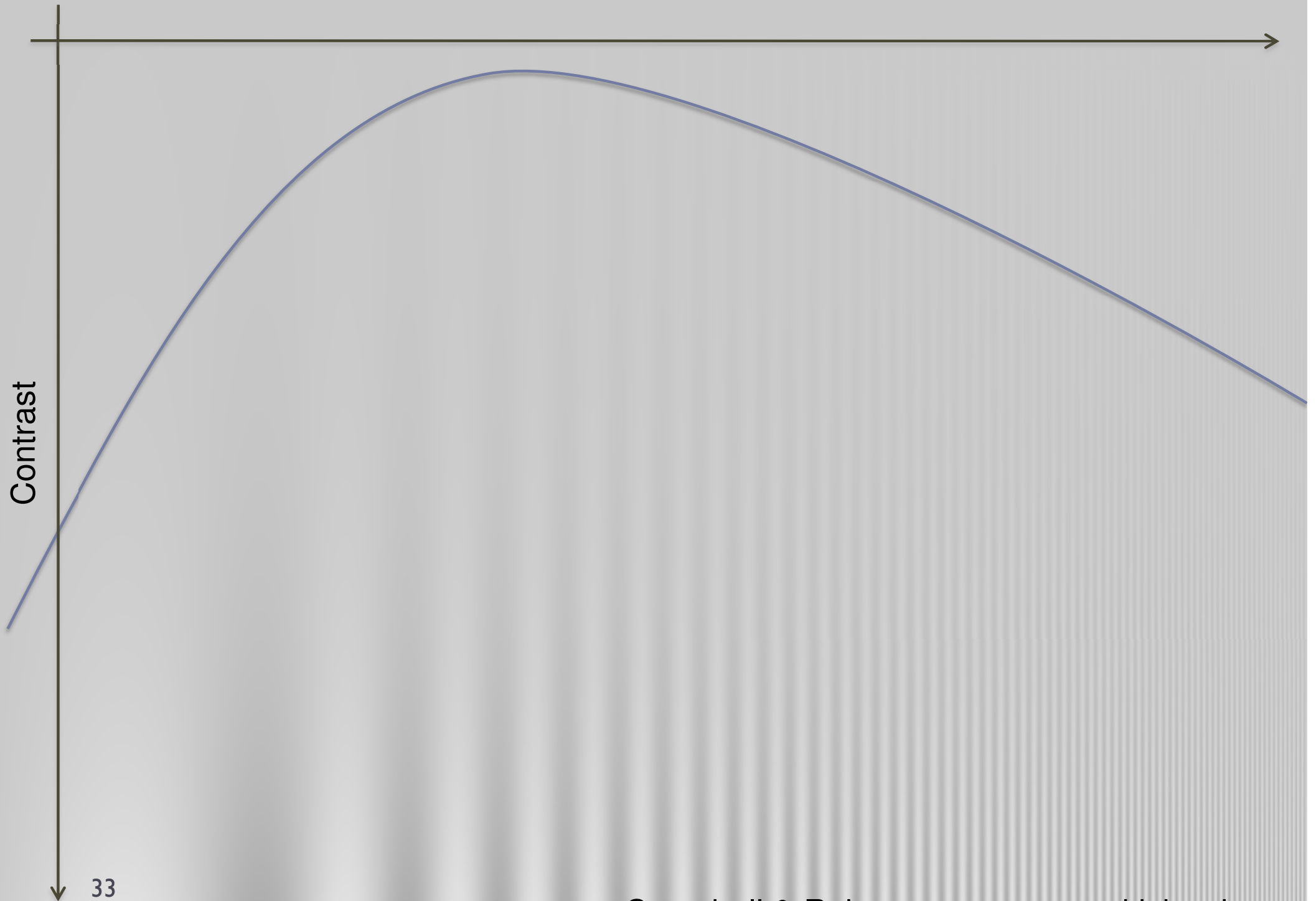
Nyquist frequency / aliasing

- ▶ Nyquist frequency is the highest frequency that can be represented by a discrete set of uniform samples (pixels)
- ▶ Nyquist 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

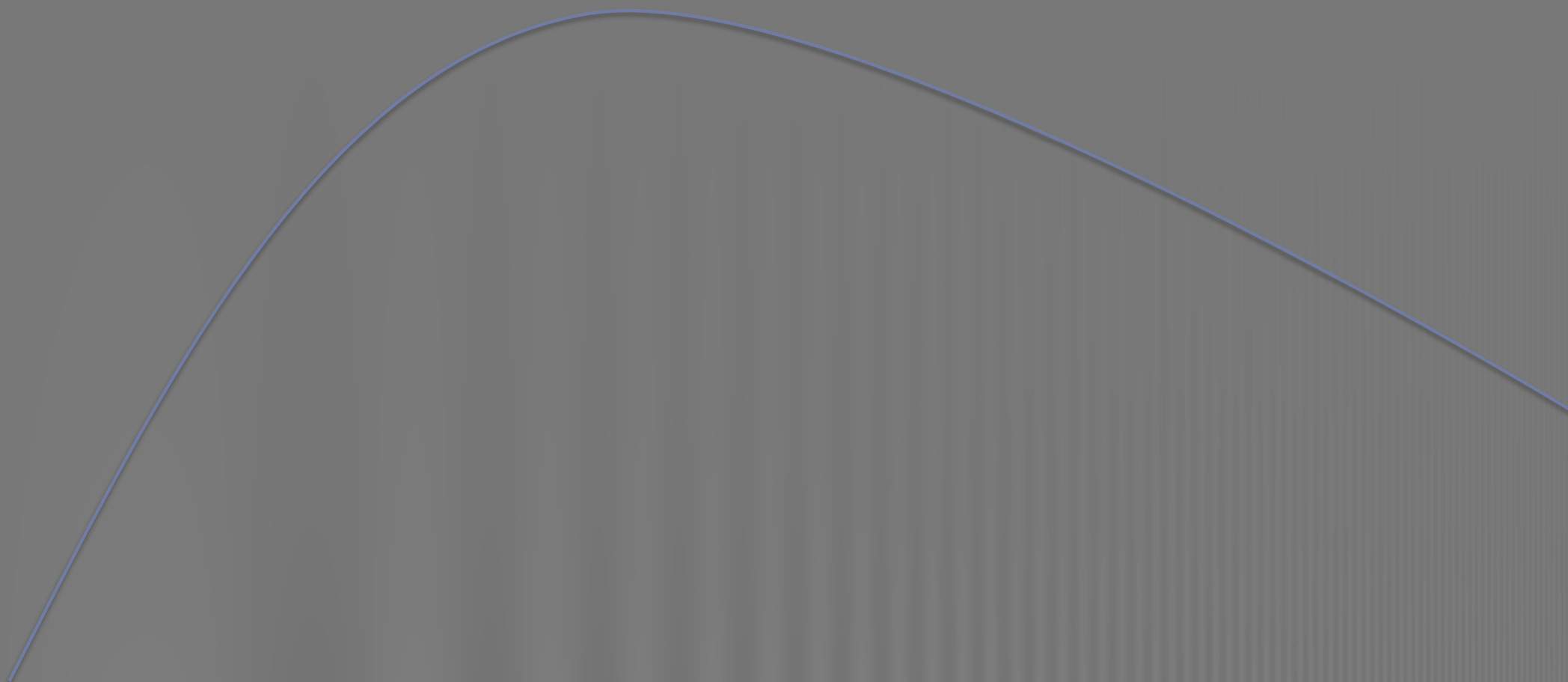
Modeling contrast detection



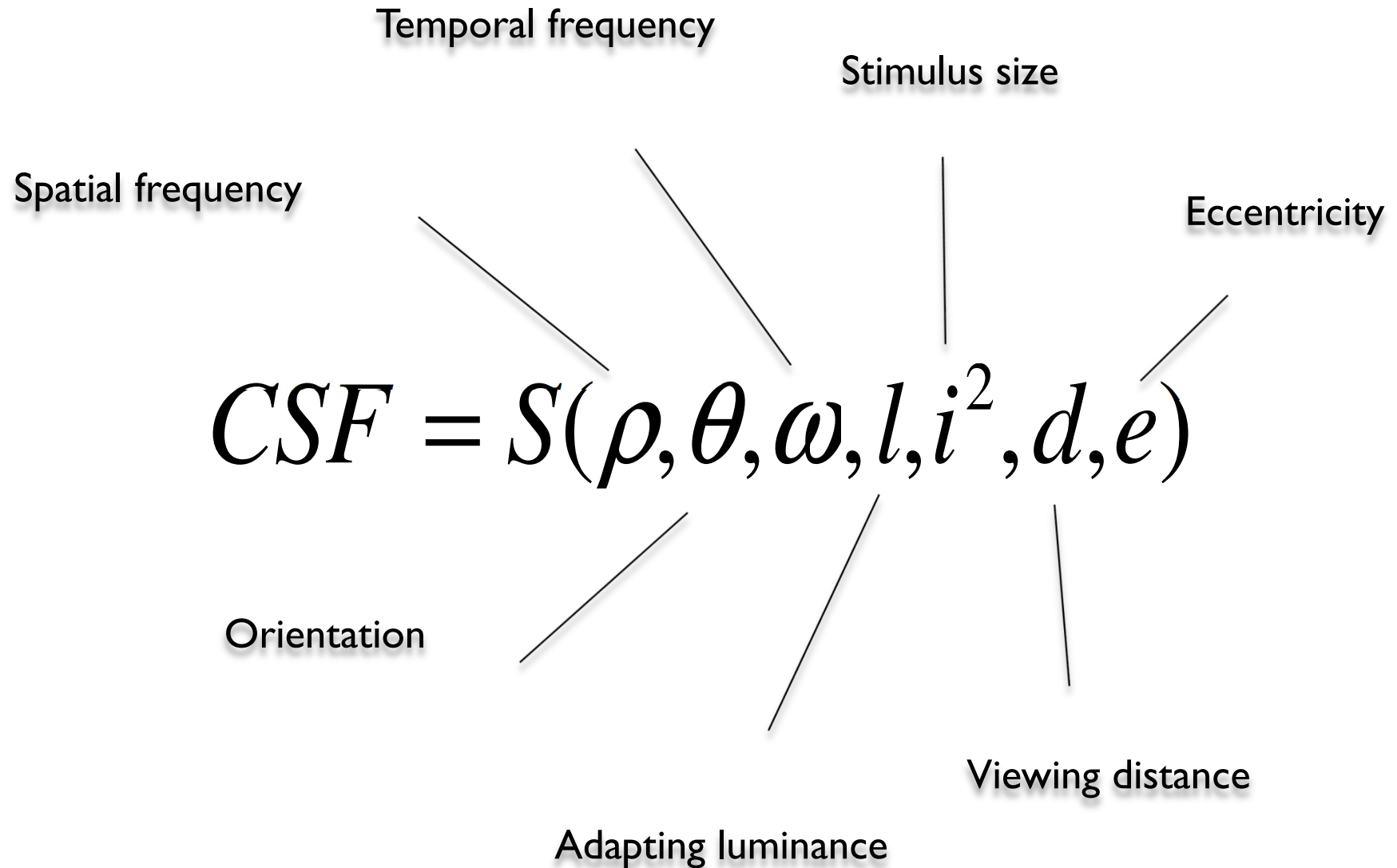
Spatial frequency [cycles per degree]



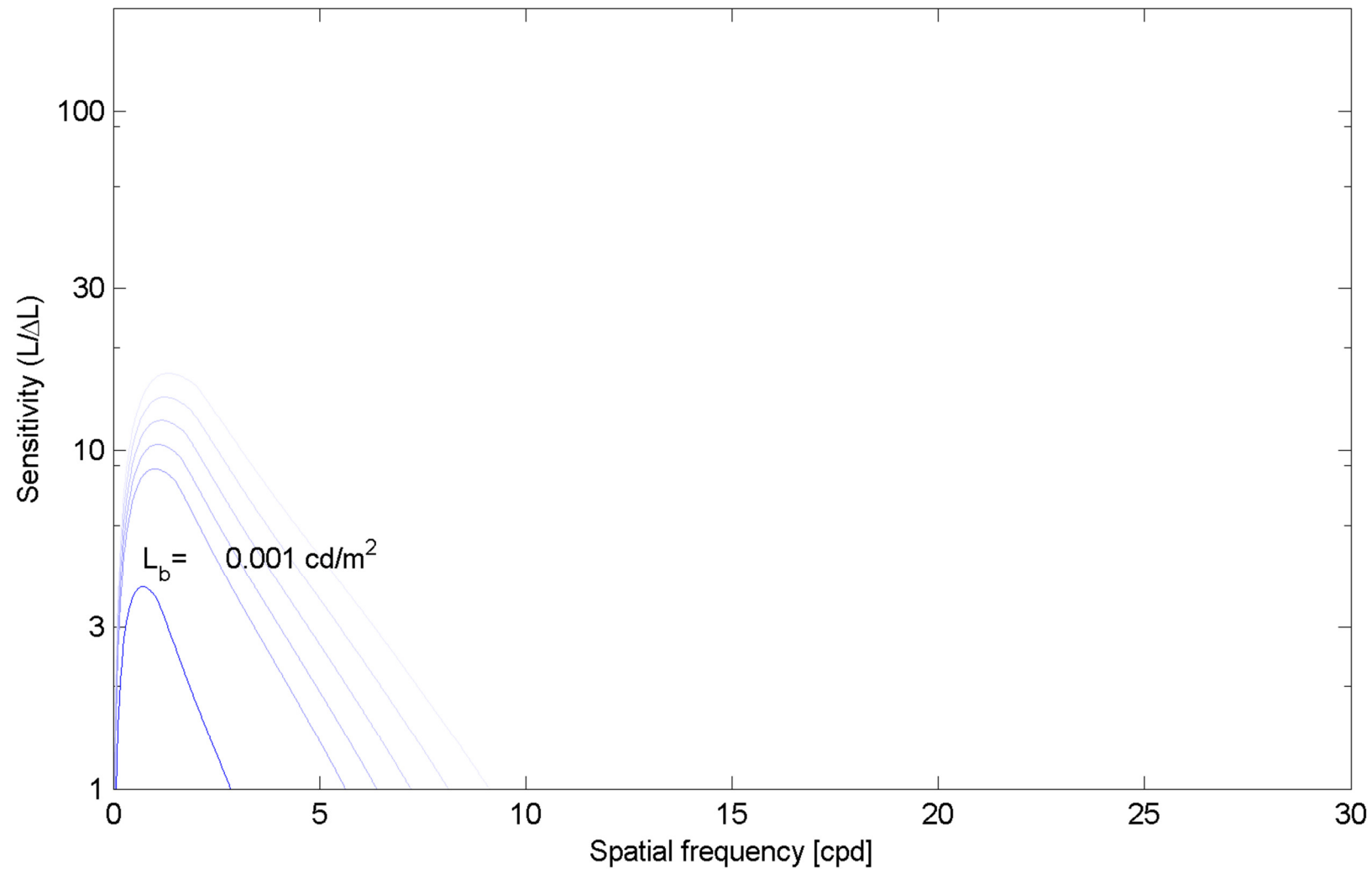
Campbell & Robson contrast sensitivity chart



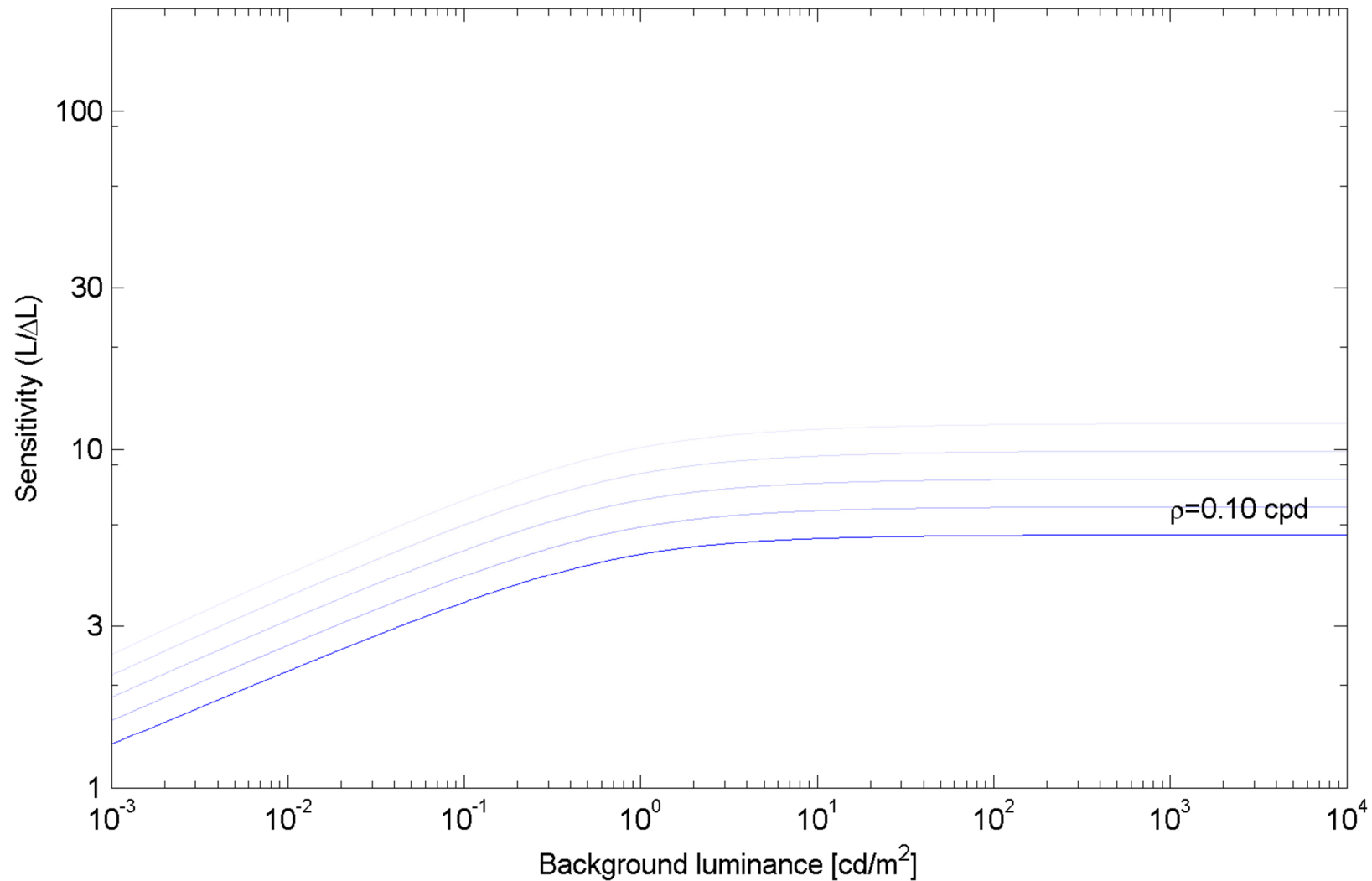
Contrast sensitivity function



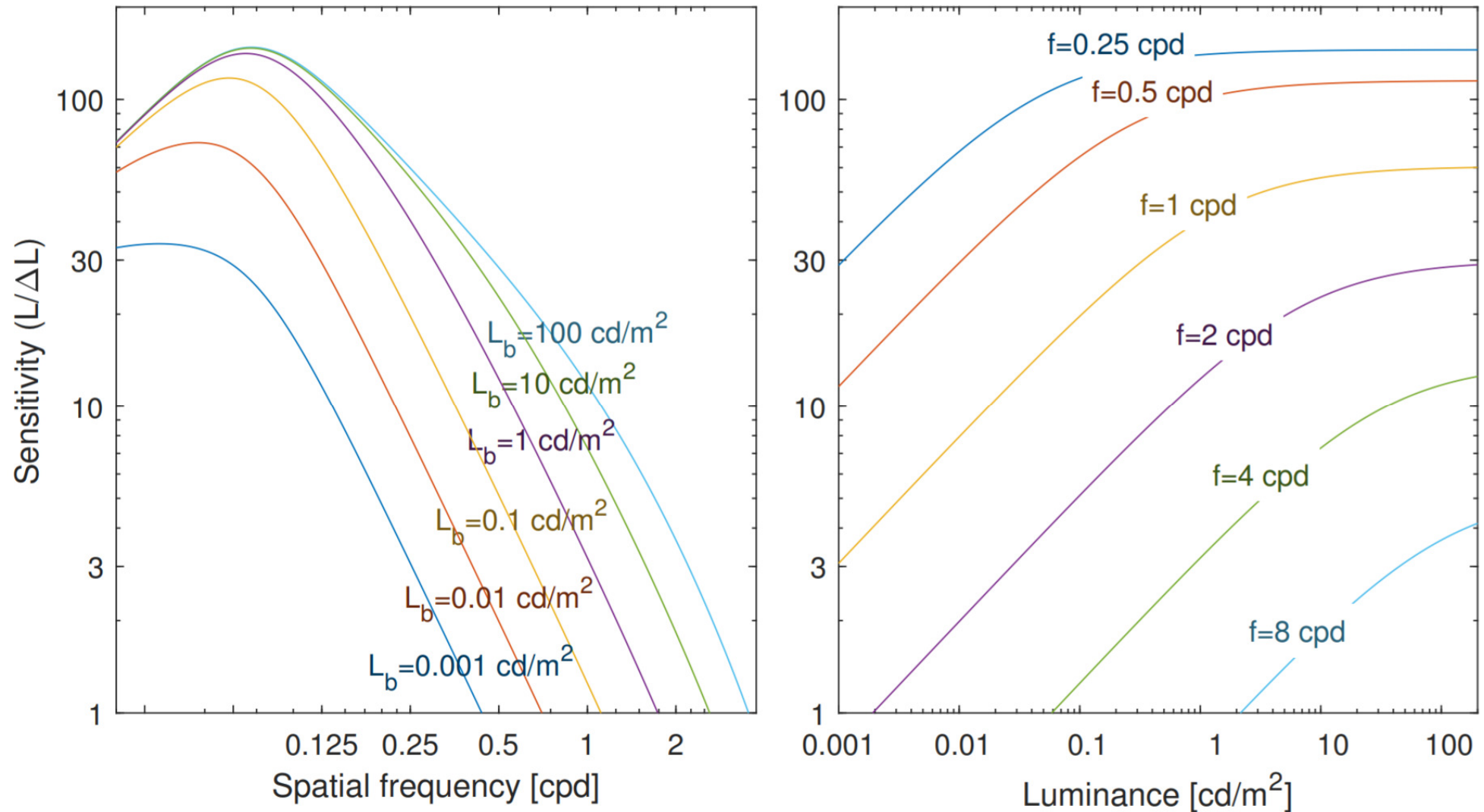
CSF as a function of spatial frequency



CSF as a function of background luminance

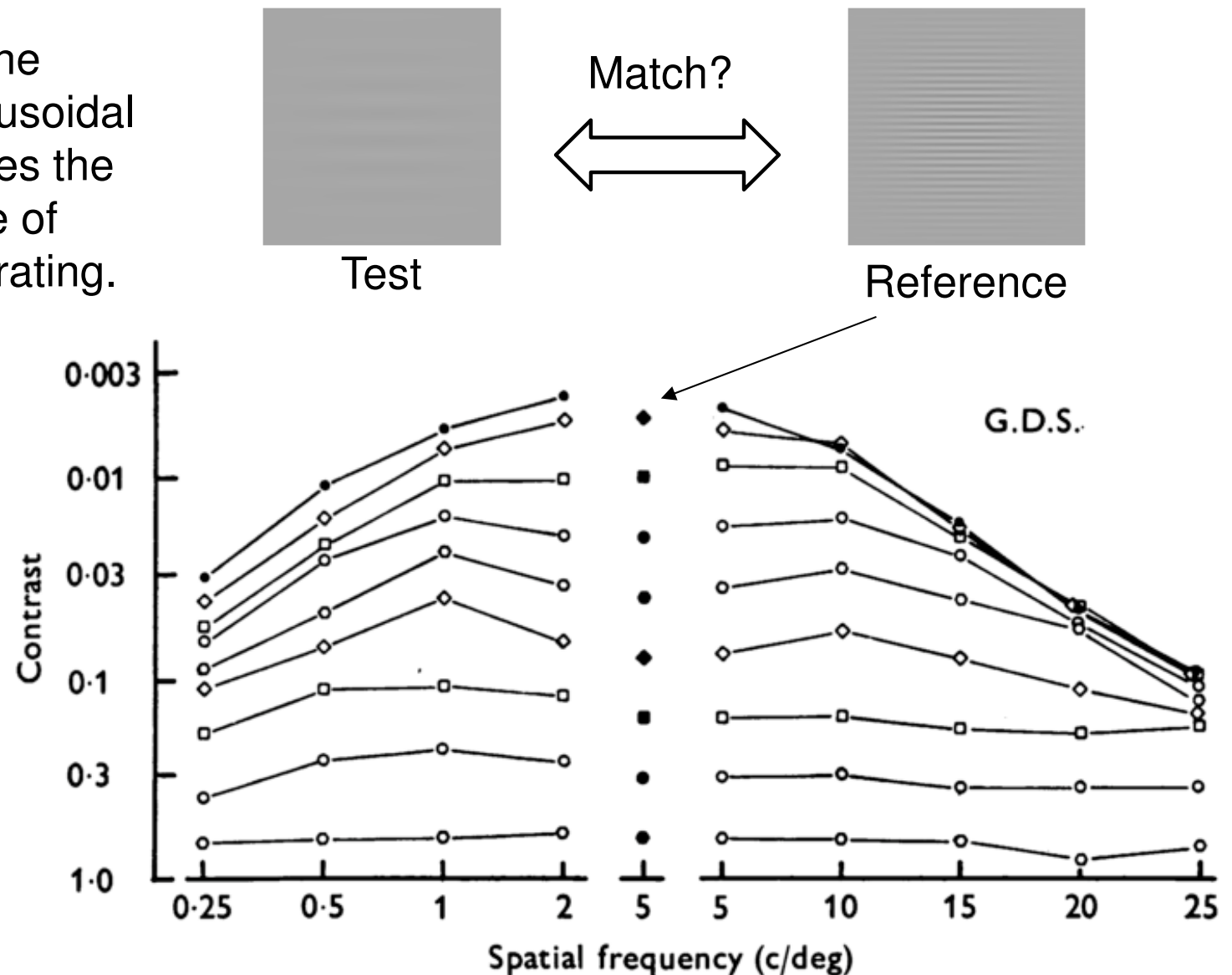


CSF as a function of spatial frequency and background luminance



Contrast constancy

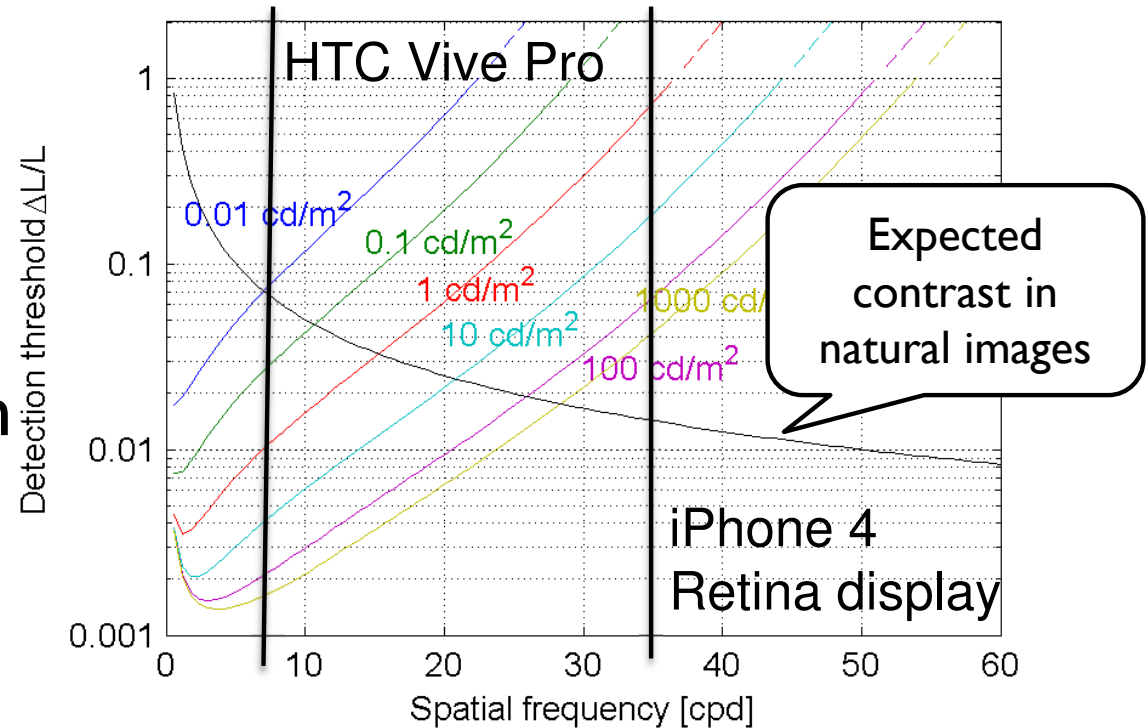
Experiment: Adjust the amplitude of one sinusoidal grating until it matches the perceived magnitude of another sinusoidal grating.



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:

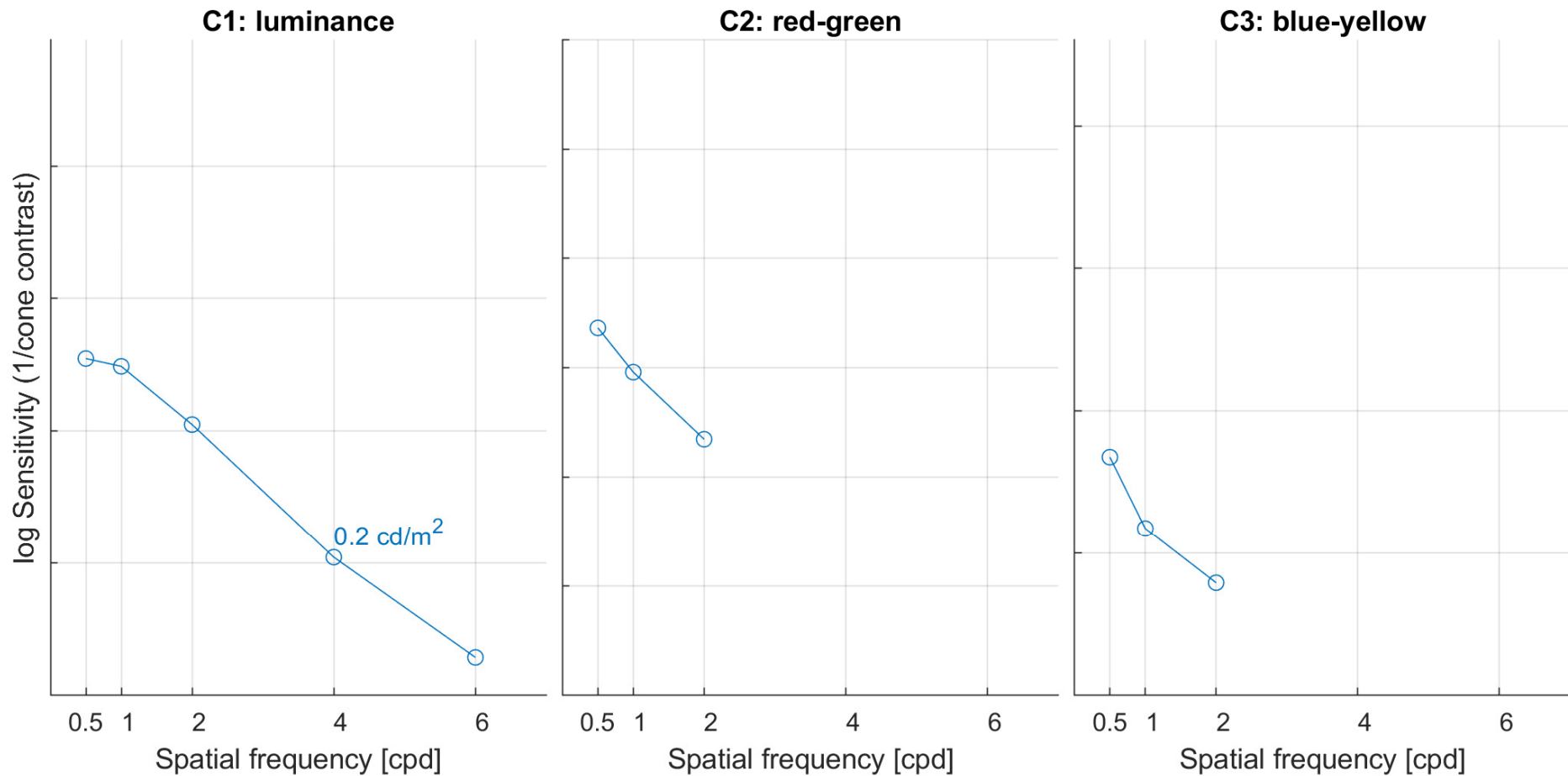
Barten, P. G. J. (2004).

<https://doi.org/10.1117/12.537476>

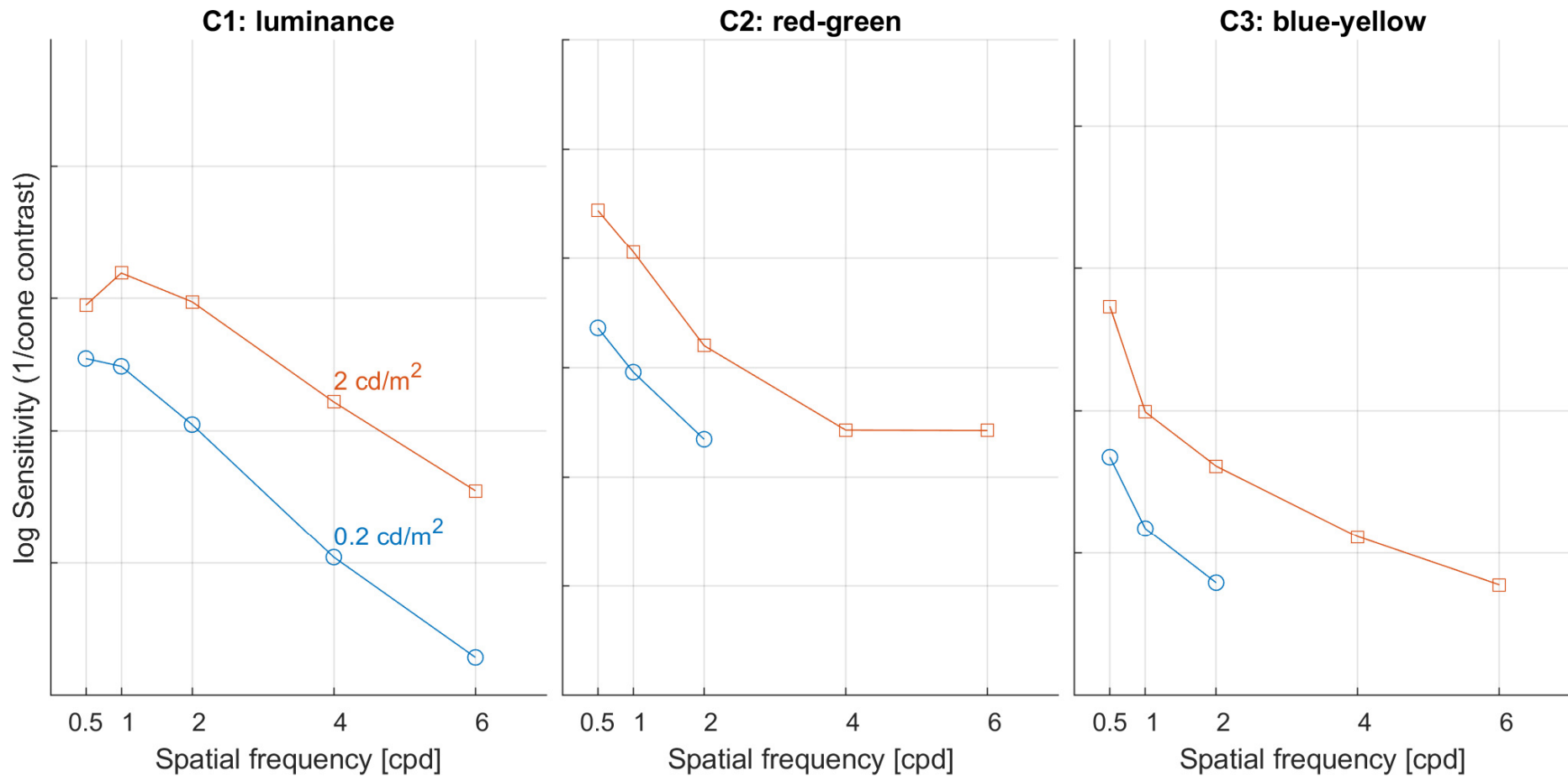
Spatio-chromatic CSF



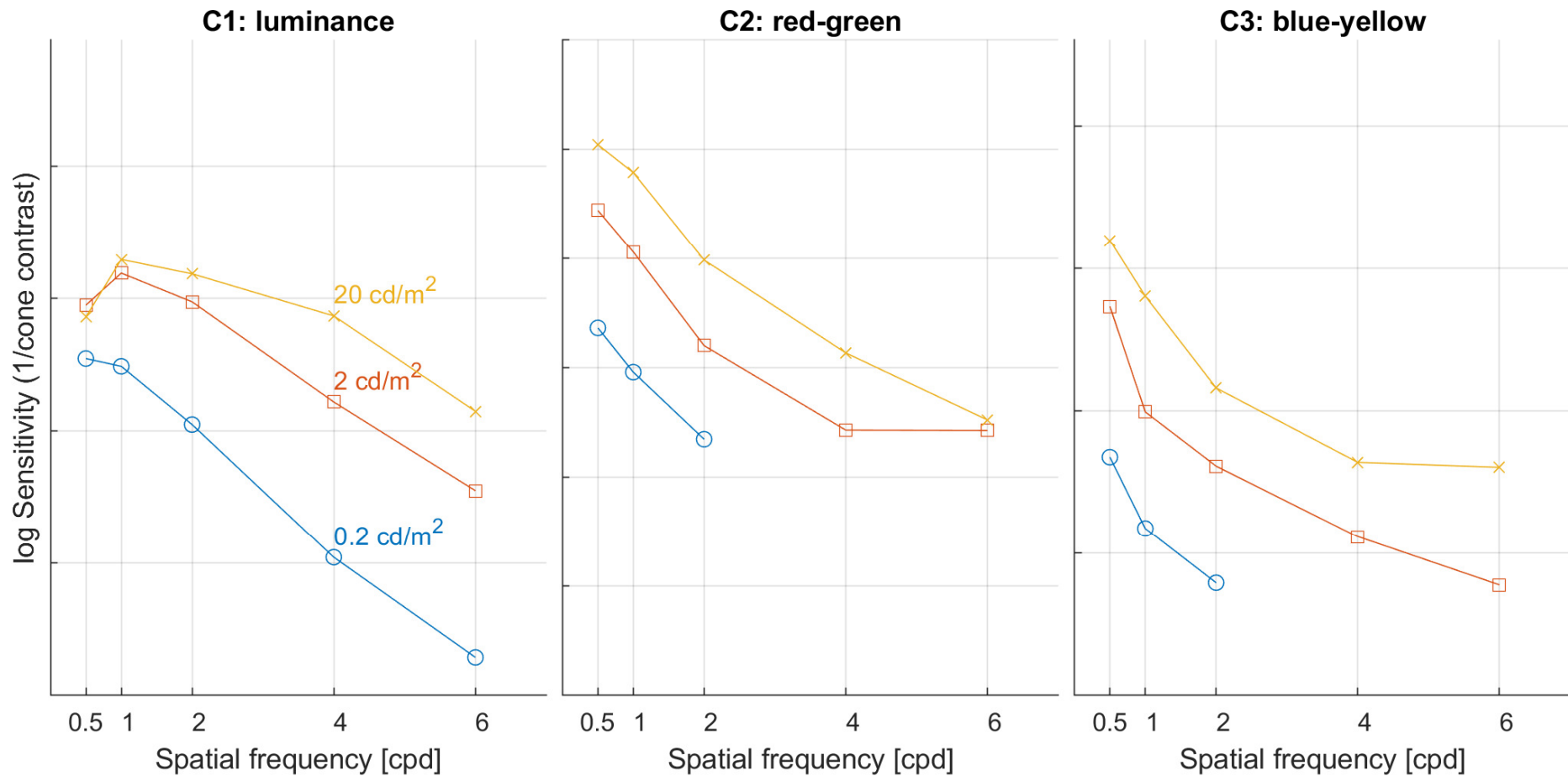
Color CSF across the luminance range



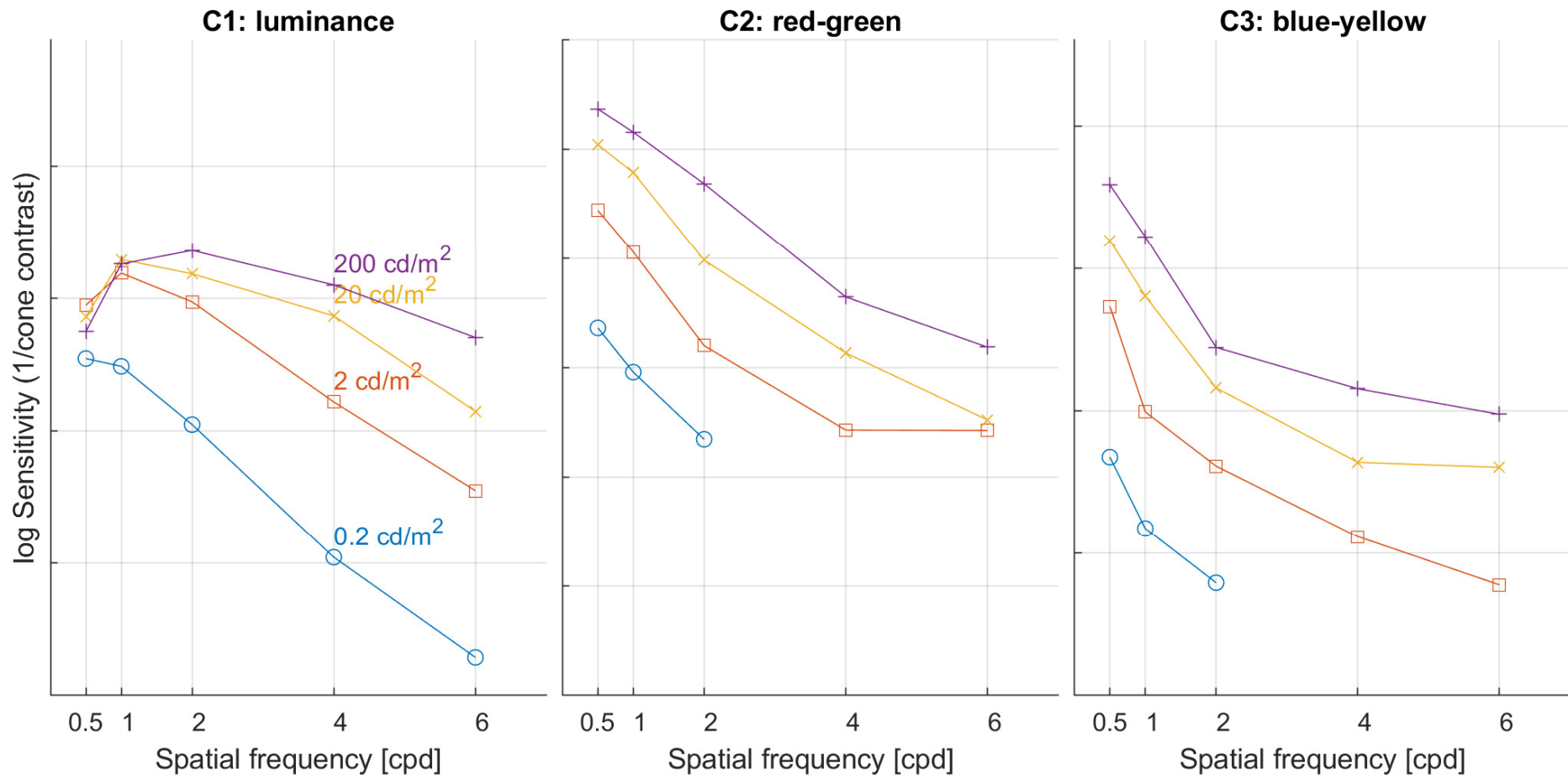
Color CSF across the luminance range



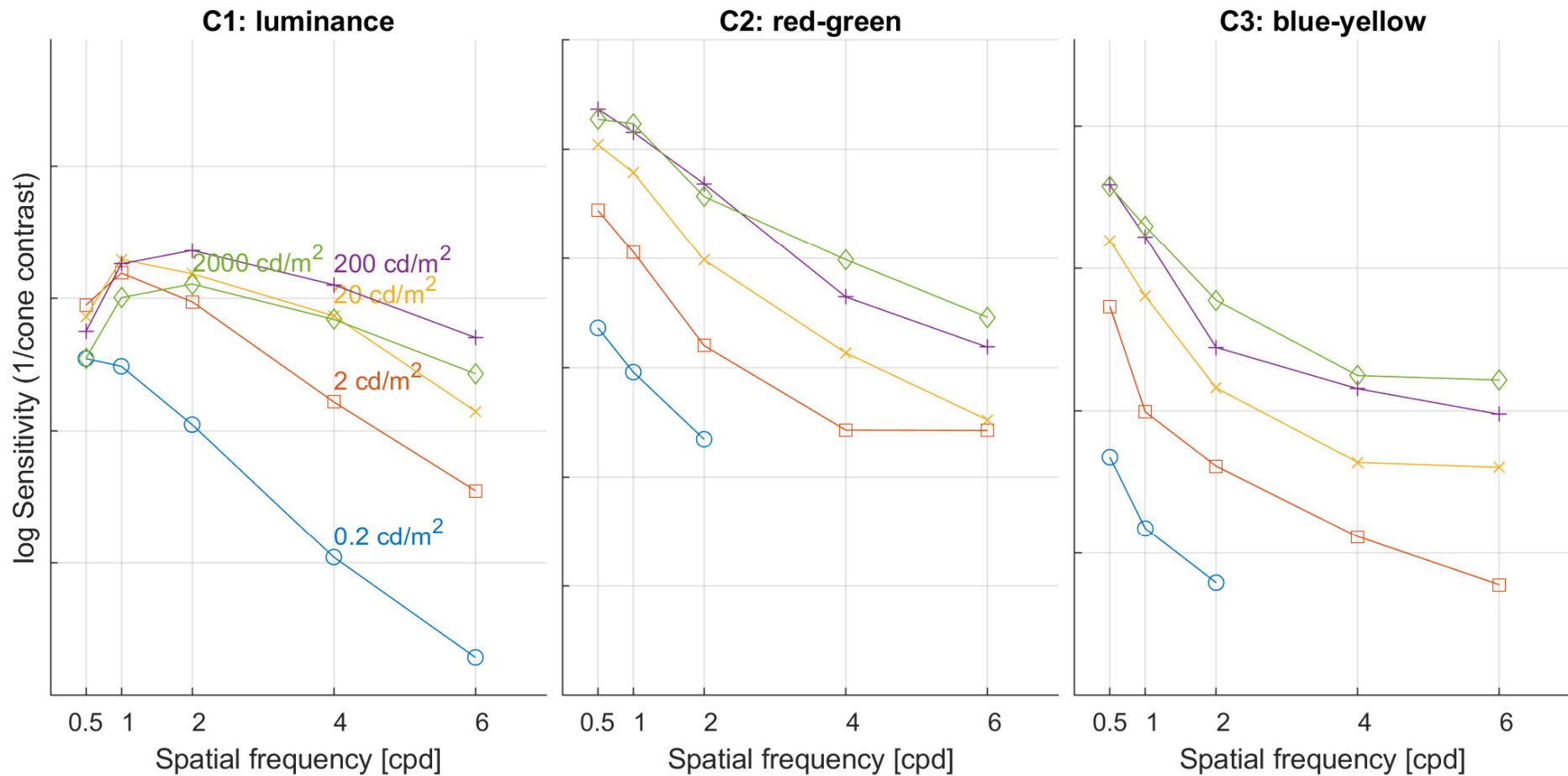
Color CSF across the luminance range



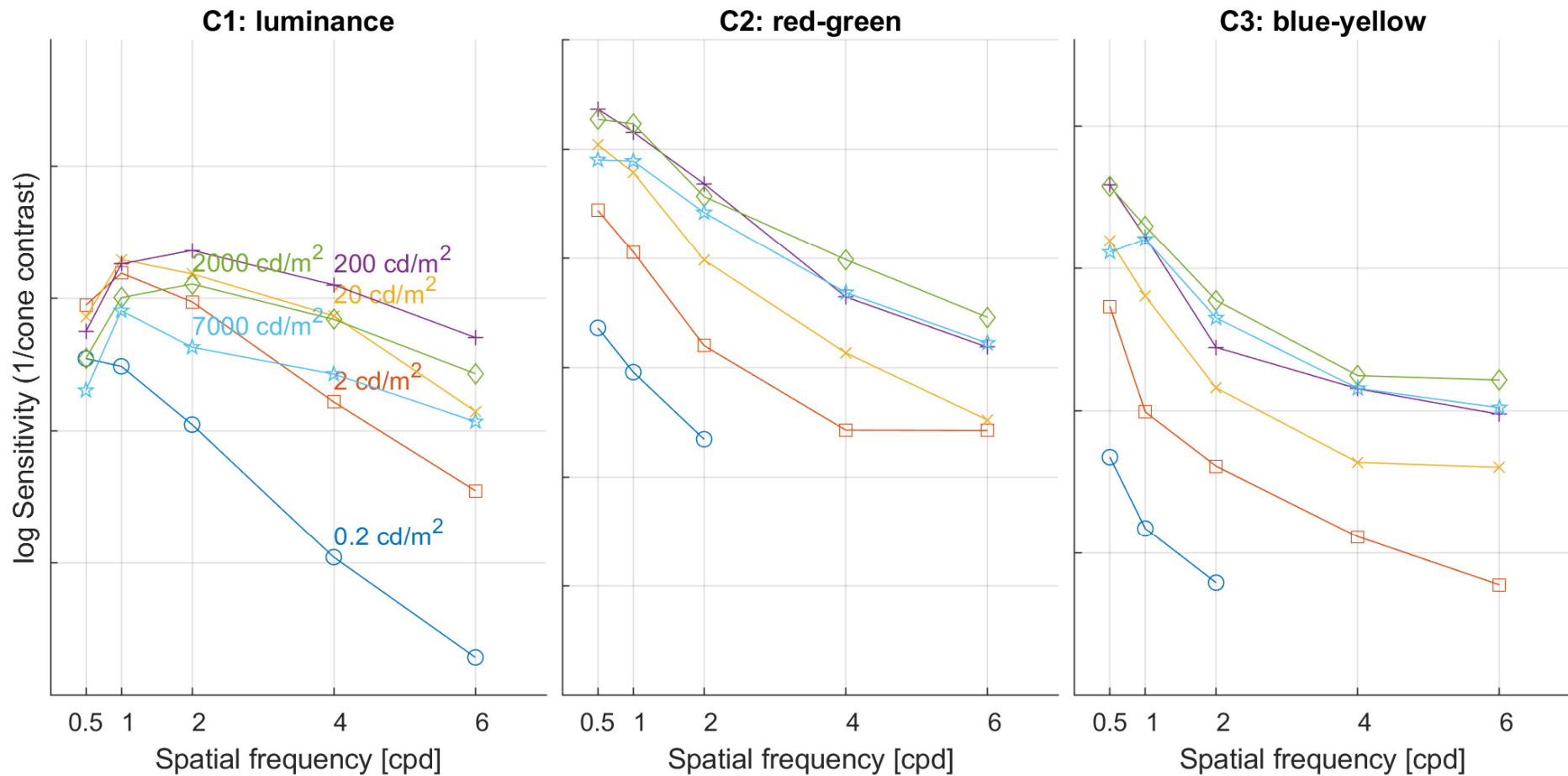
Color CSF across the luminance range



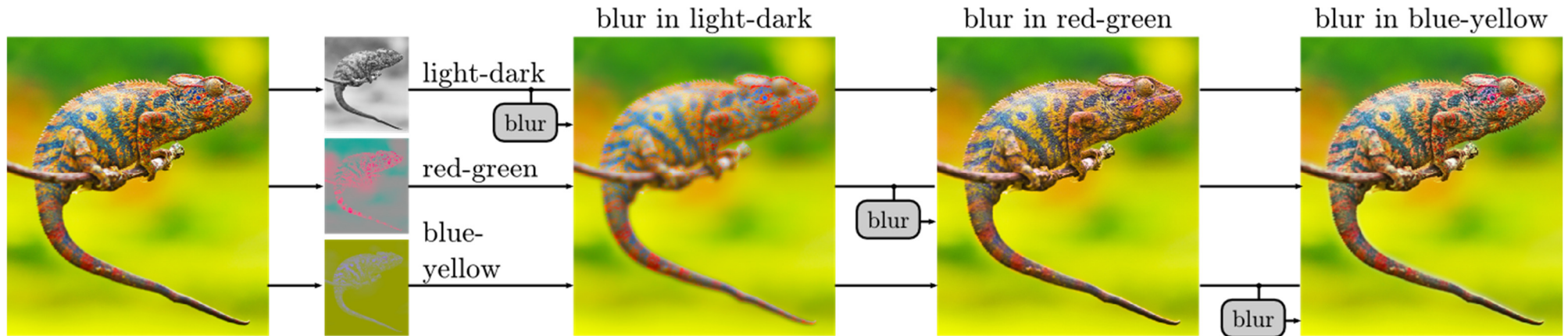
Color CSF across the luminance range



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)

Advanced Graphics and Image Processing

Models of early visual perception

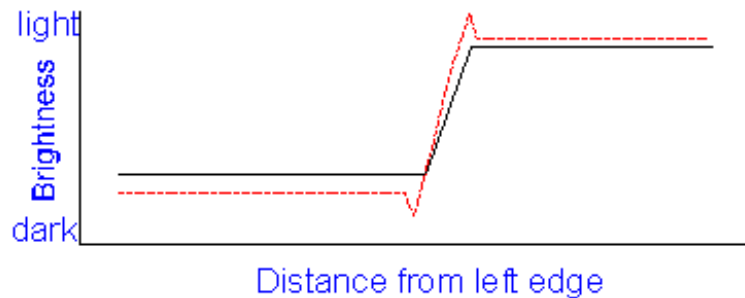
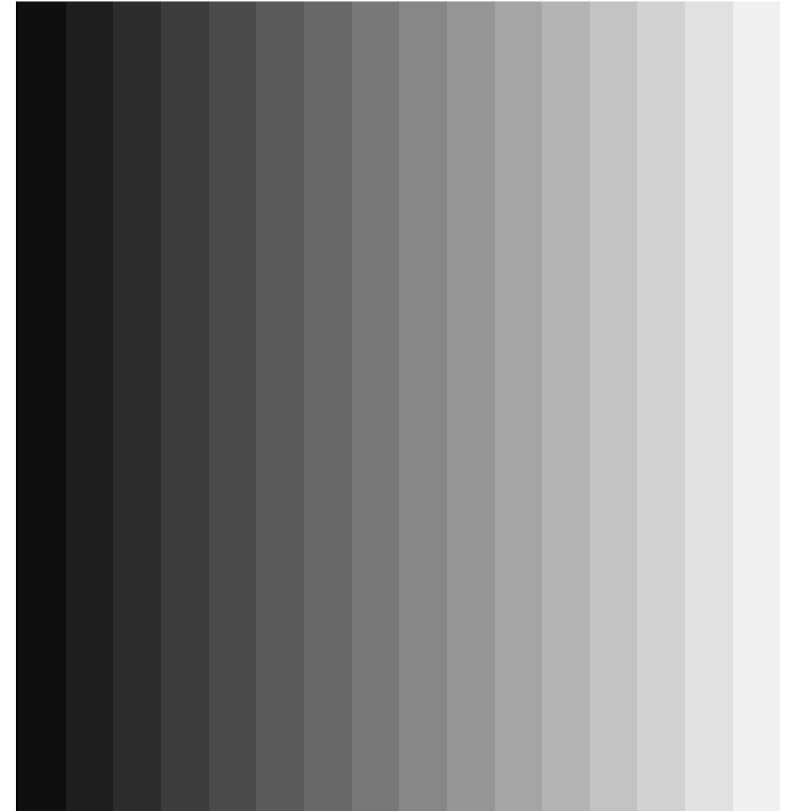
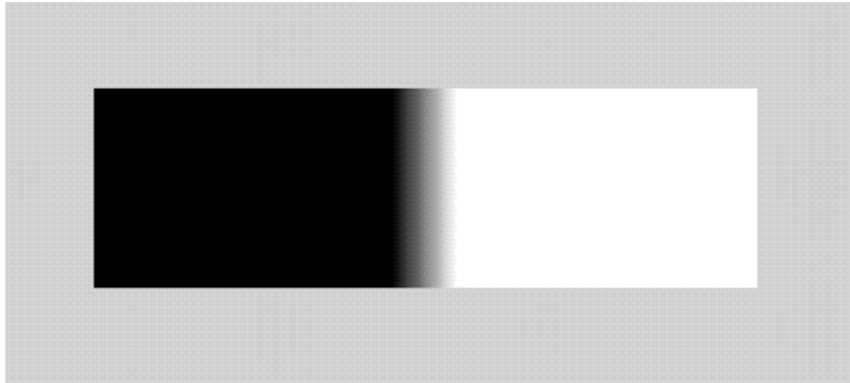
Part 4/6 – lateral inhibition and multi-resolution models

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Mach Bands – evidence for band-pass visual processing

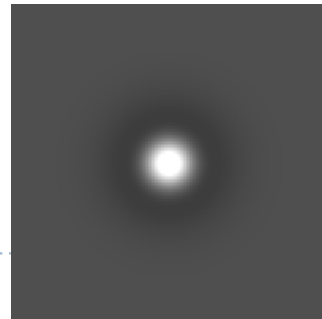
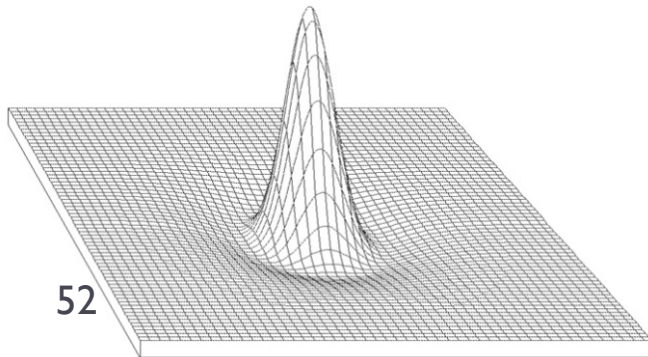
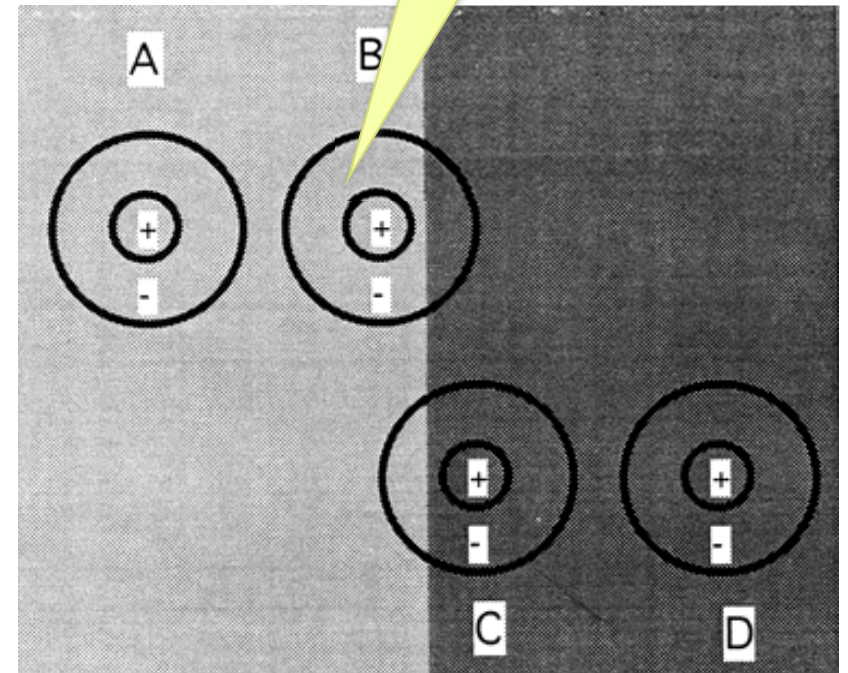
- “Overshooting” along edges
 - Extra-bright rims on bright sides
 - Extra-dark rims on dark sides
- Due to “Lateral Inhibition”



Centre-surround (Lateral Inhibition)

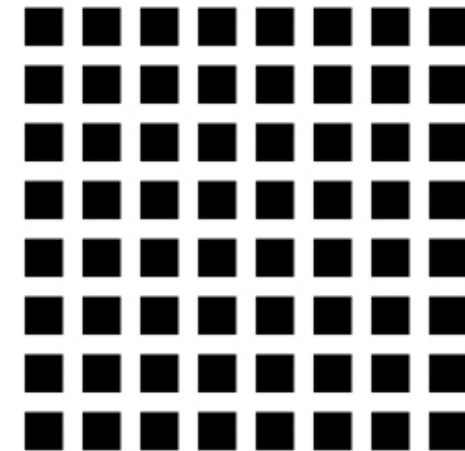
- ▶ “Pre-processing” step within the retina
 - ▶ Surrounding brightness level weighted negatively
 - ▶ A: high stimulus, maximal bright inhibition
 - ▶ B: high stimulus, reduced inhibition & stronger response
 - ▶ D: low stimulus, maximal inhibition
 - ▶ C: low stimulus, increased inhibition & weaker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

Center-surround
receptive fields
(groups of
photoreceptors)



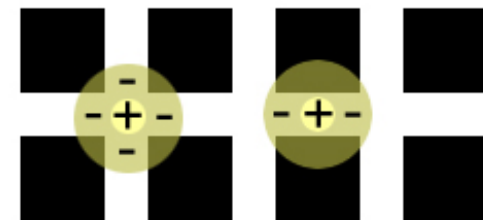
Centre-surround: Hermann Grid

- 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 ?



A

B



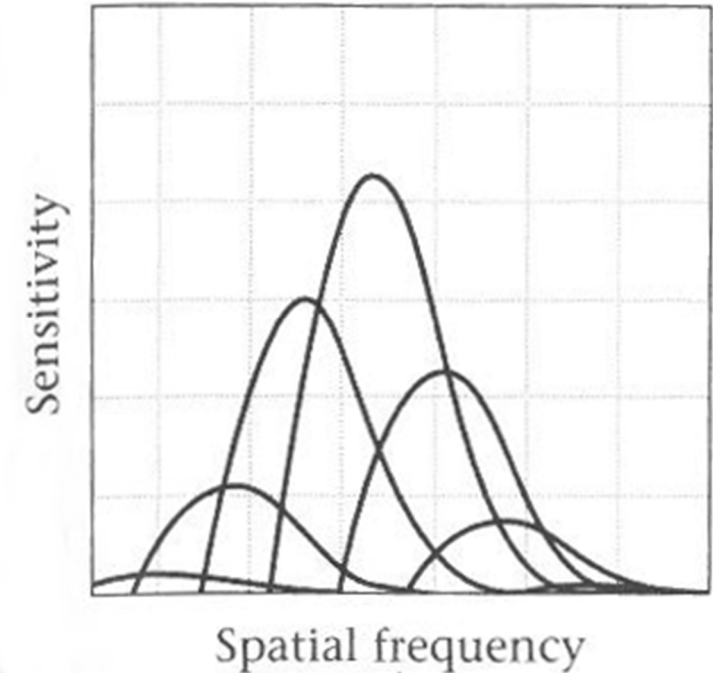
Simulation



some further weirdness

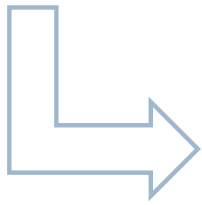
Spatial-frequency selective channels

- ▶ 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

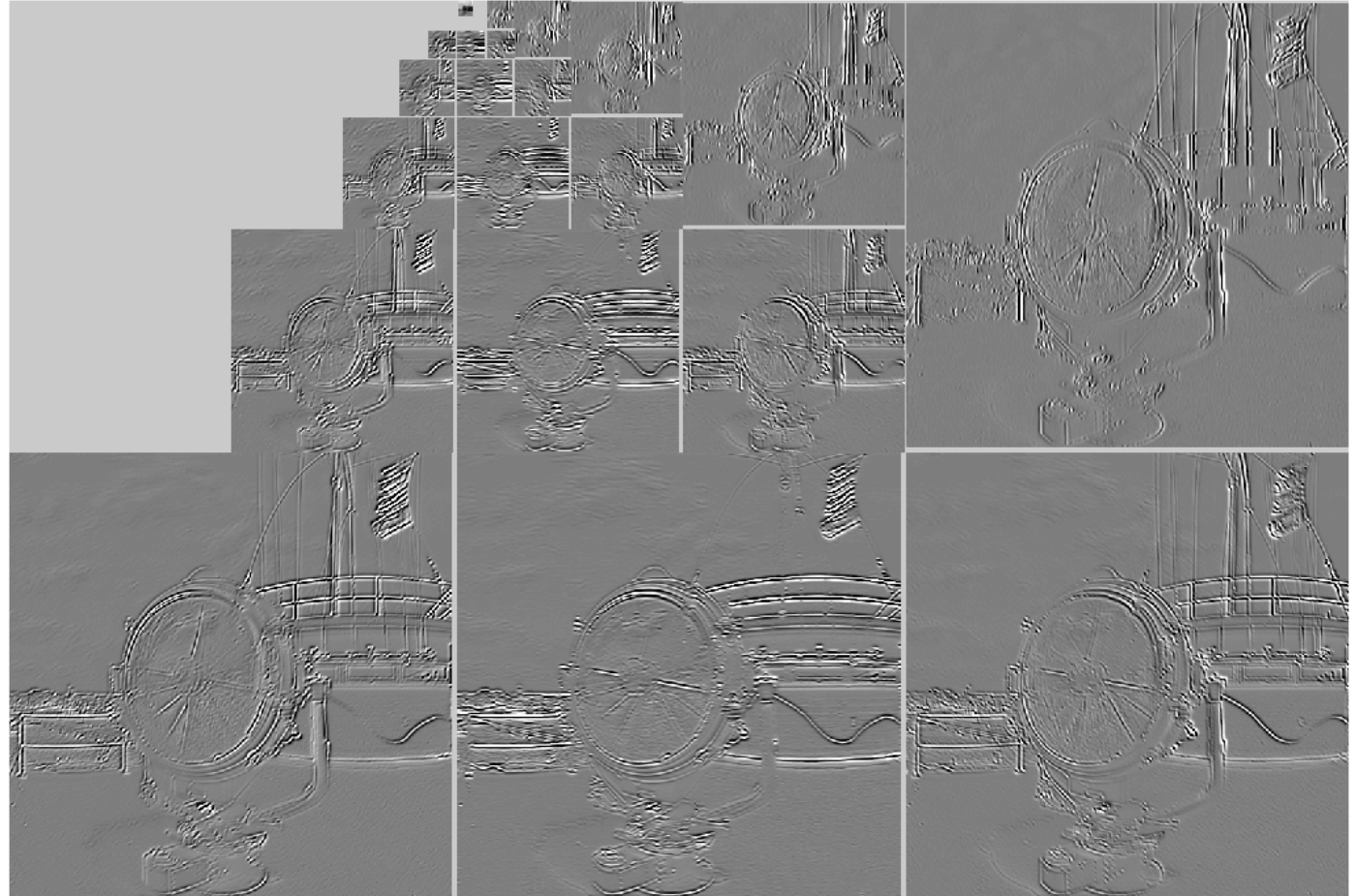


From: Wandell, 1995

Multi-scale decomposition

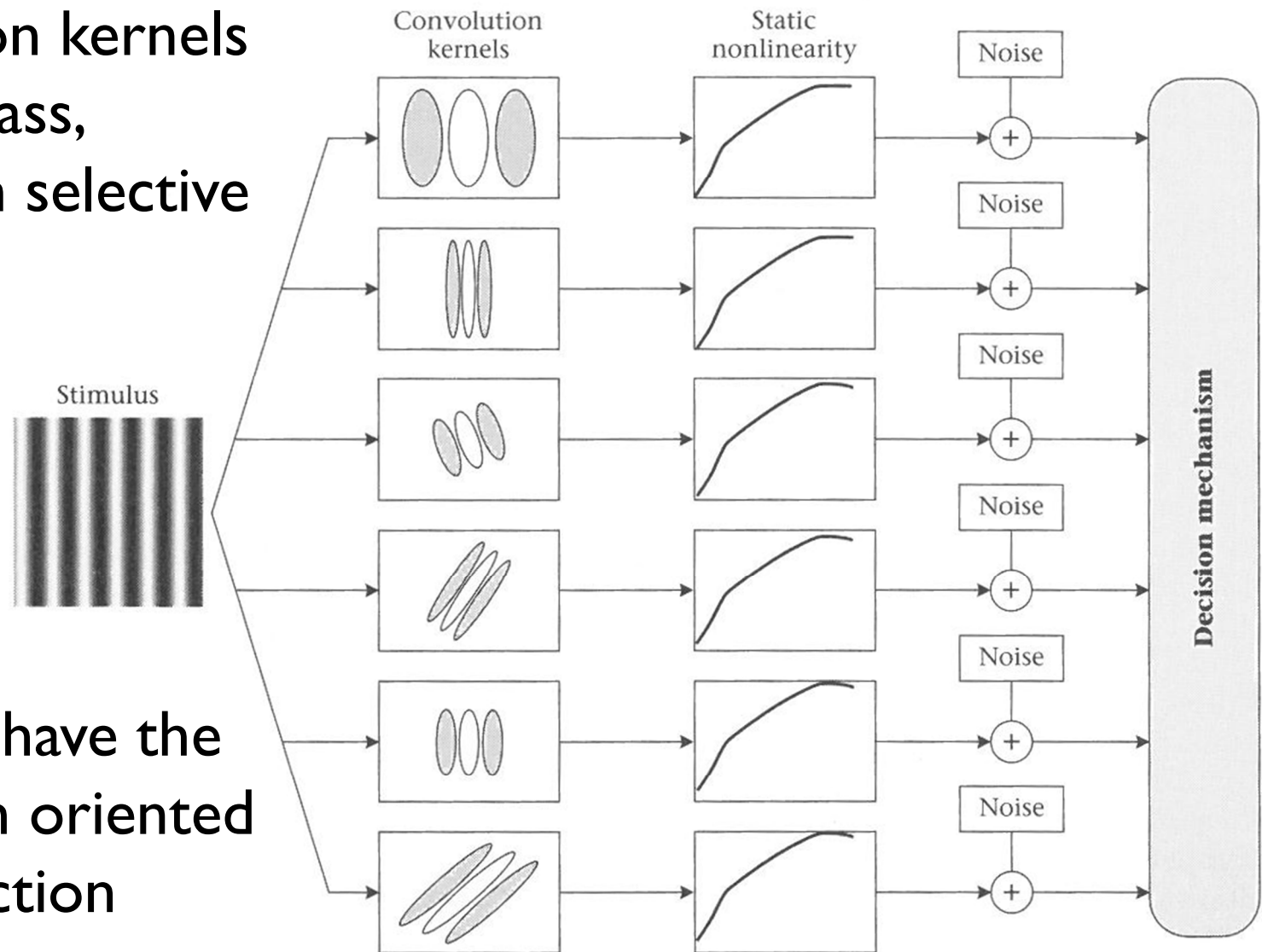


Steerable pyramid
decomposition



Multi-resolution visual model

- Convolution kernels are band-pass, orientation selective filters



- The filters have the shape of an oriented Gabor function

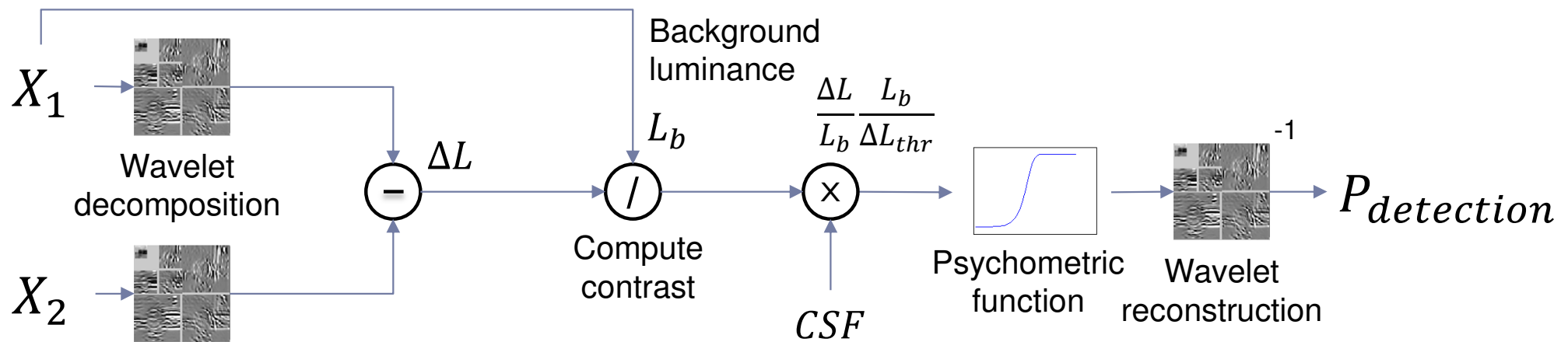
From: Wandell, 1995

Predicting visible differences with CSF

- ▶ We can use CSF to find the probability of spotting a difference between 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

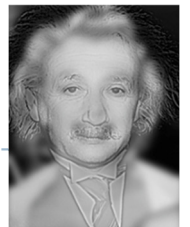
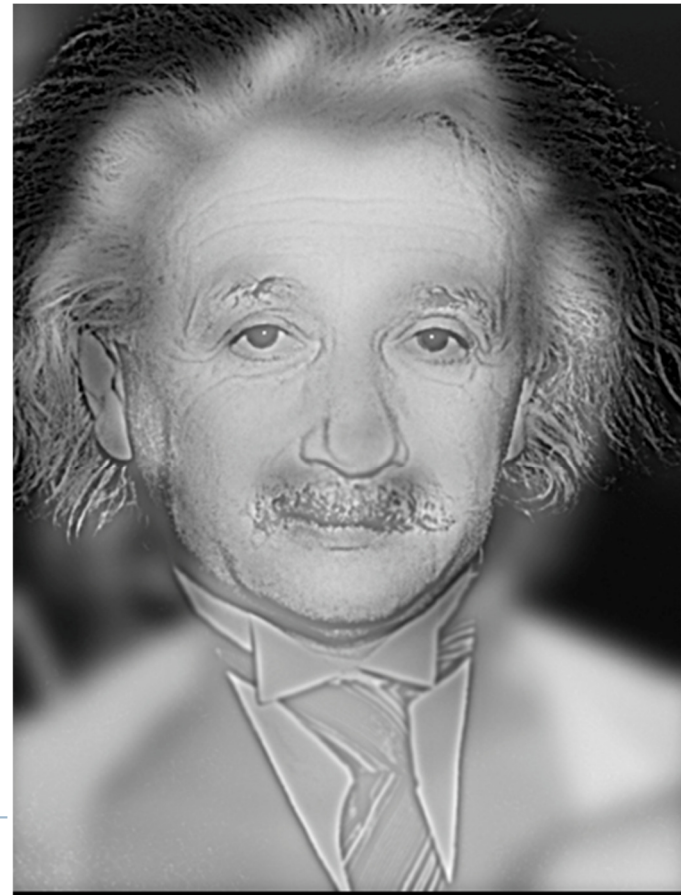


- ▶ **JPEG / MPEG**

- ▶ Frequency transforms

- ▶ **Image pyramids**

- ▶ Blending & stitching
 - ▶ Hybrid images



Advanced Graphics and Image Processing

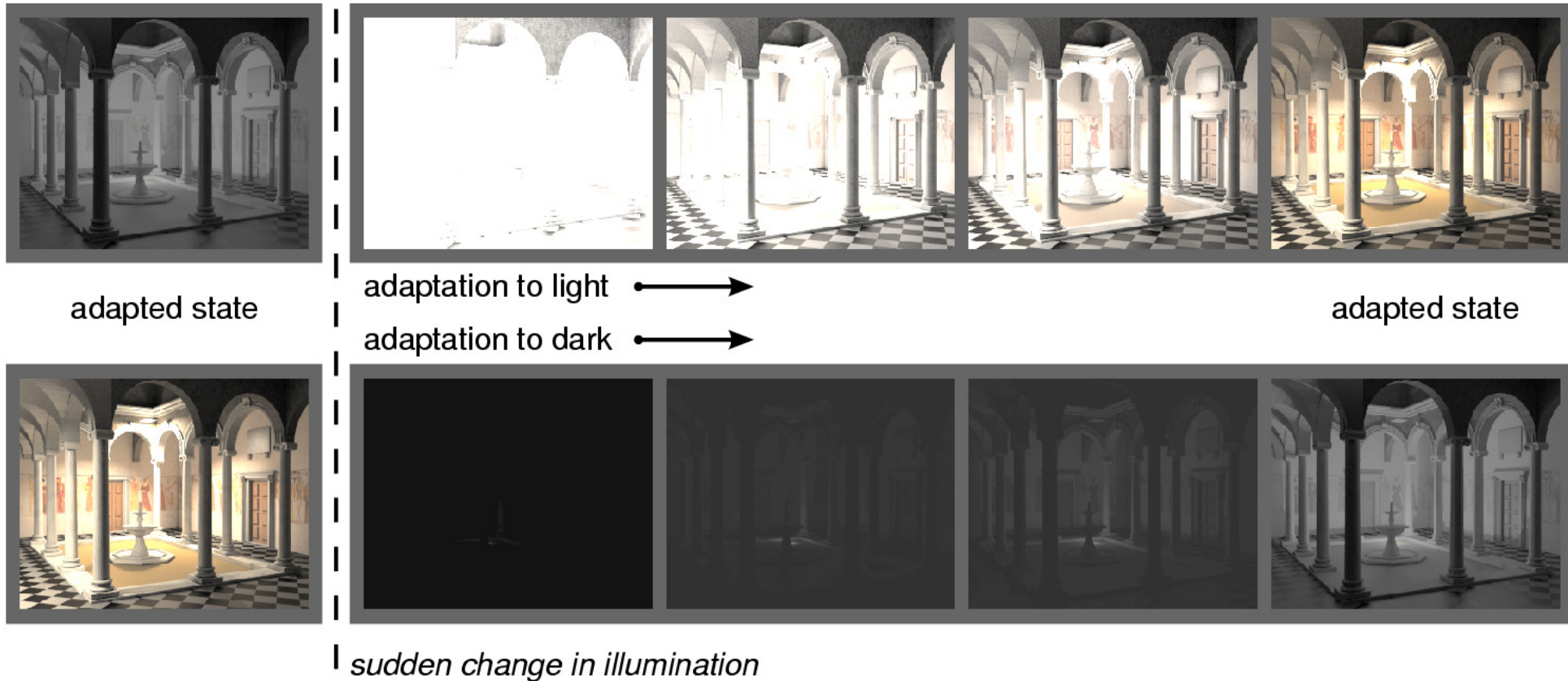
Models of early visual perception

Part 5/6 – light and dark adaptation

Rafal Mantiuk

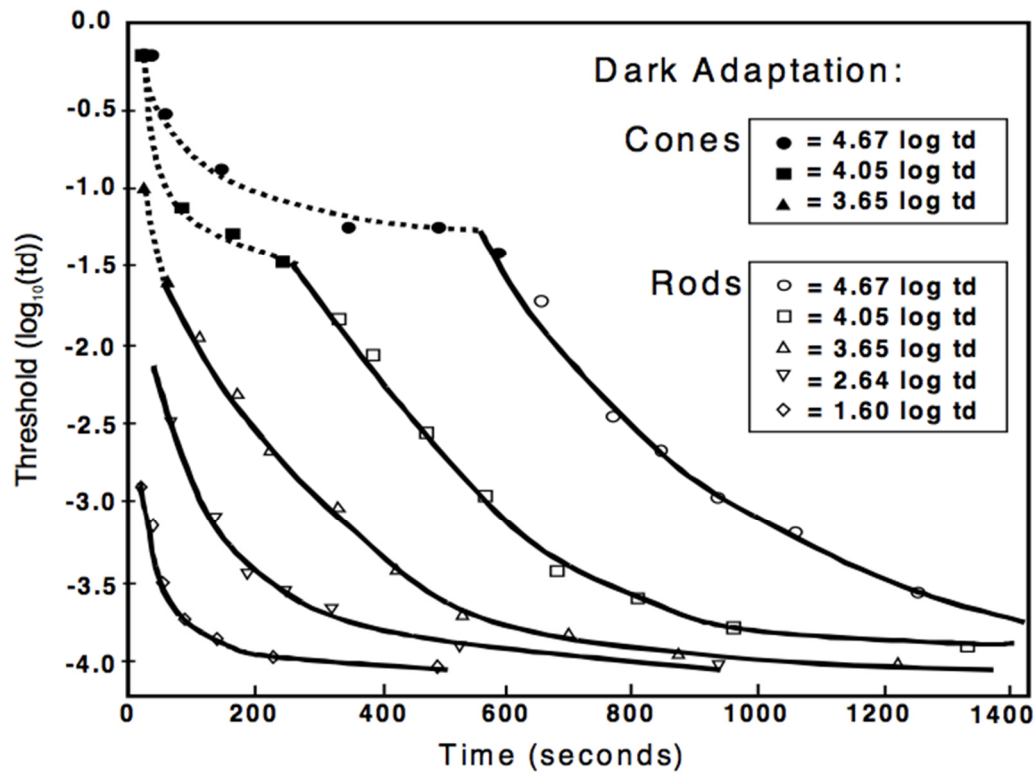
Computer Laboratory, University of Cambridge

Light and dark adaptation

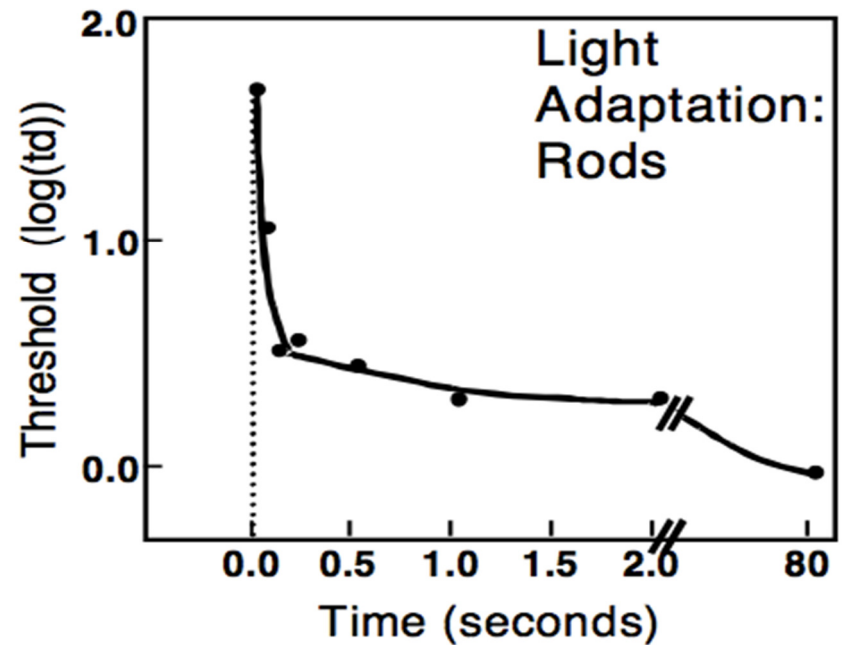
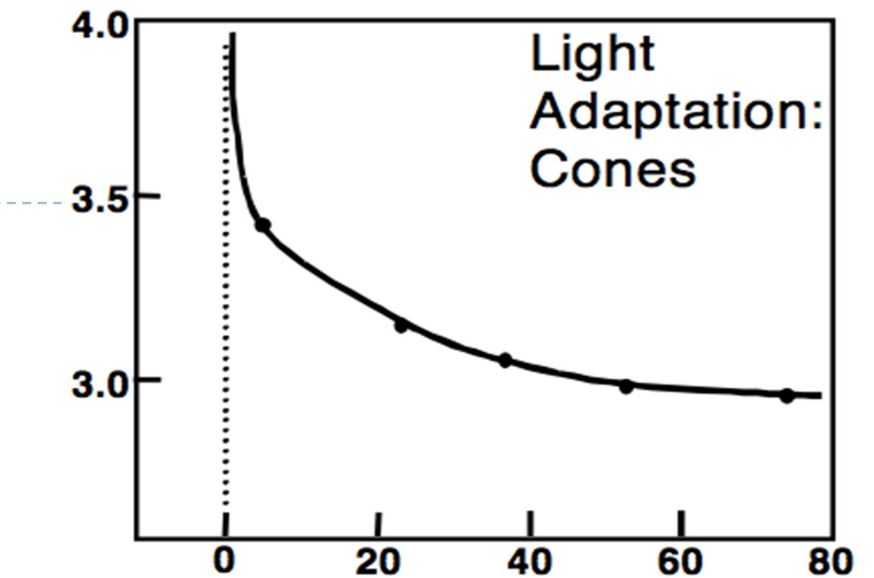


- ▶ Light adaptation: from dark to bright
- ▶ Dark adaptation: from bright to dark (much slower)

Time-course of adaptation



Bright \rightarrow Dark



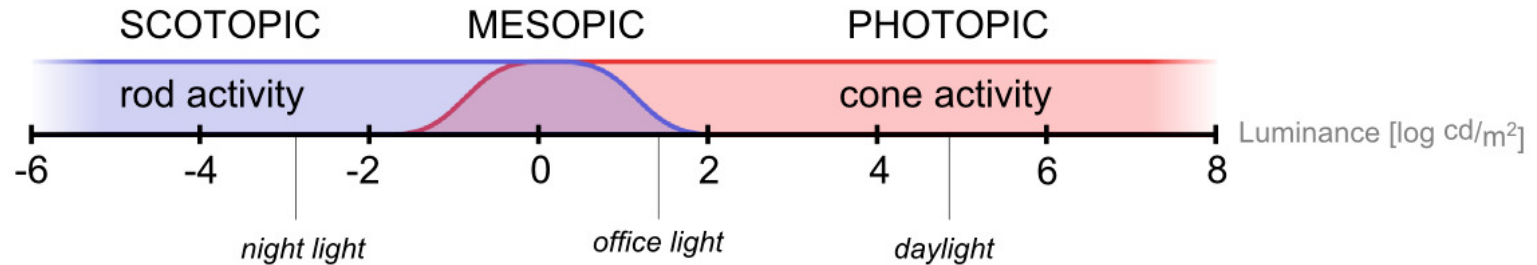
Dark \rightarrow Bright

Temporal adaptation mechanisms

- ▶ **Bleaching & recovery of photopigment**
 - ▶ Slow asymmetric (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 illumination

Night and daylight vision

Vision mode:

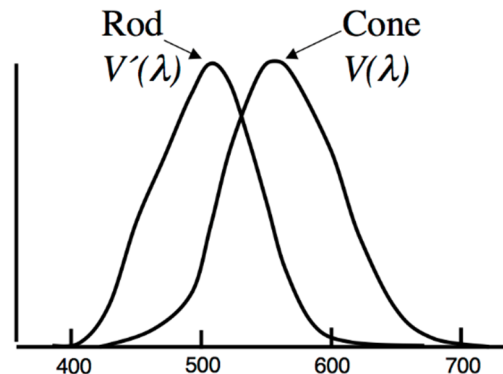


Mode properties: monochromatic vision
limited visual acuity

good color perception
good visual acuity



Luminous efficiency



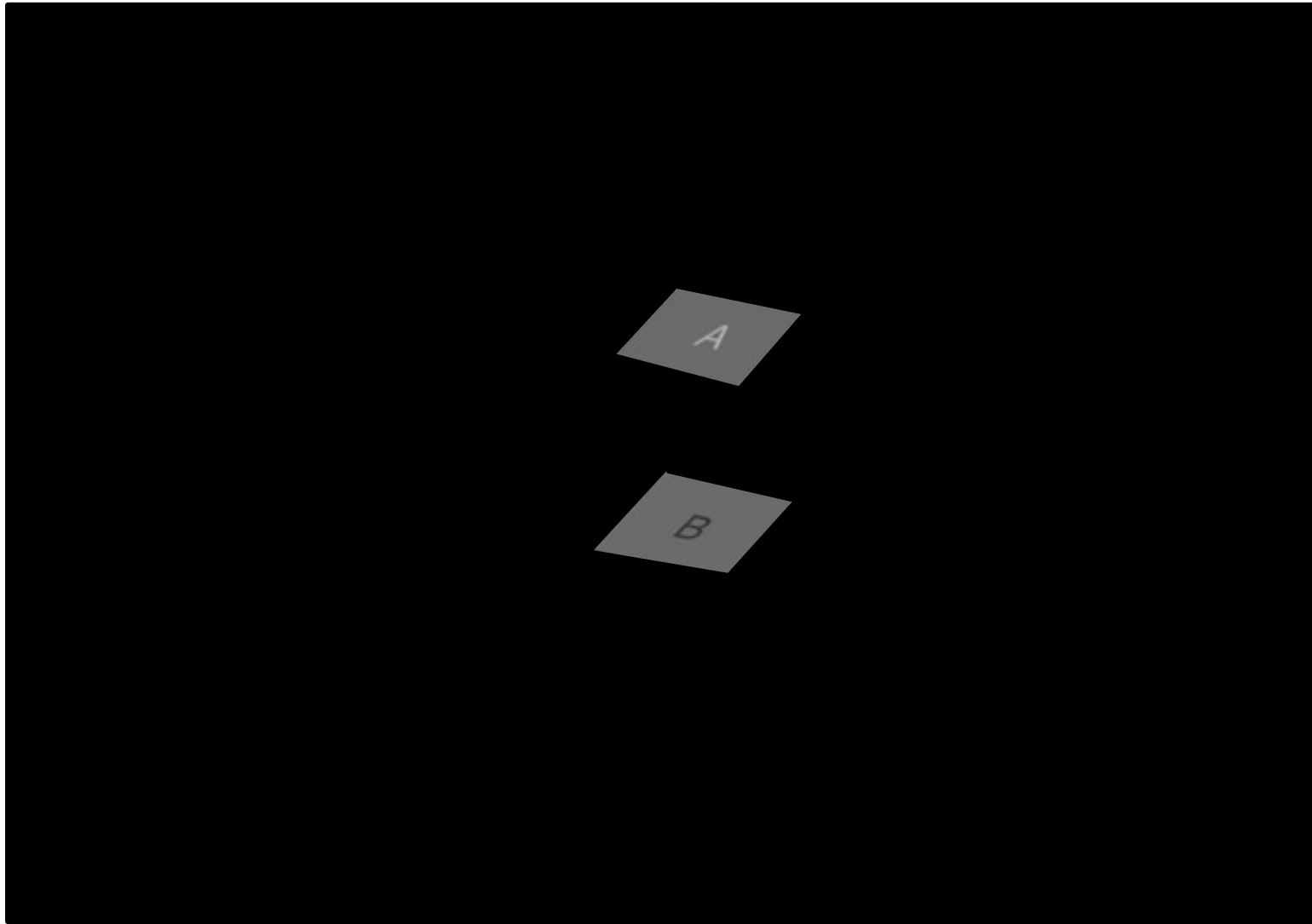
Part 6/6 – high(er) level vision

Computer Laboratory, University of Cambridge

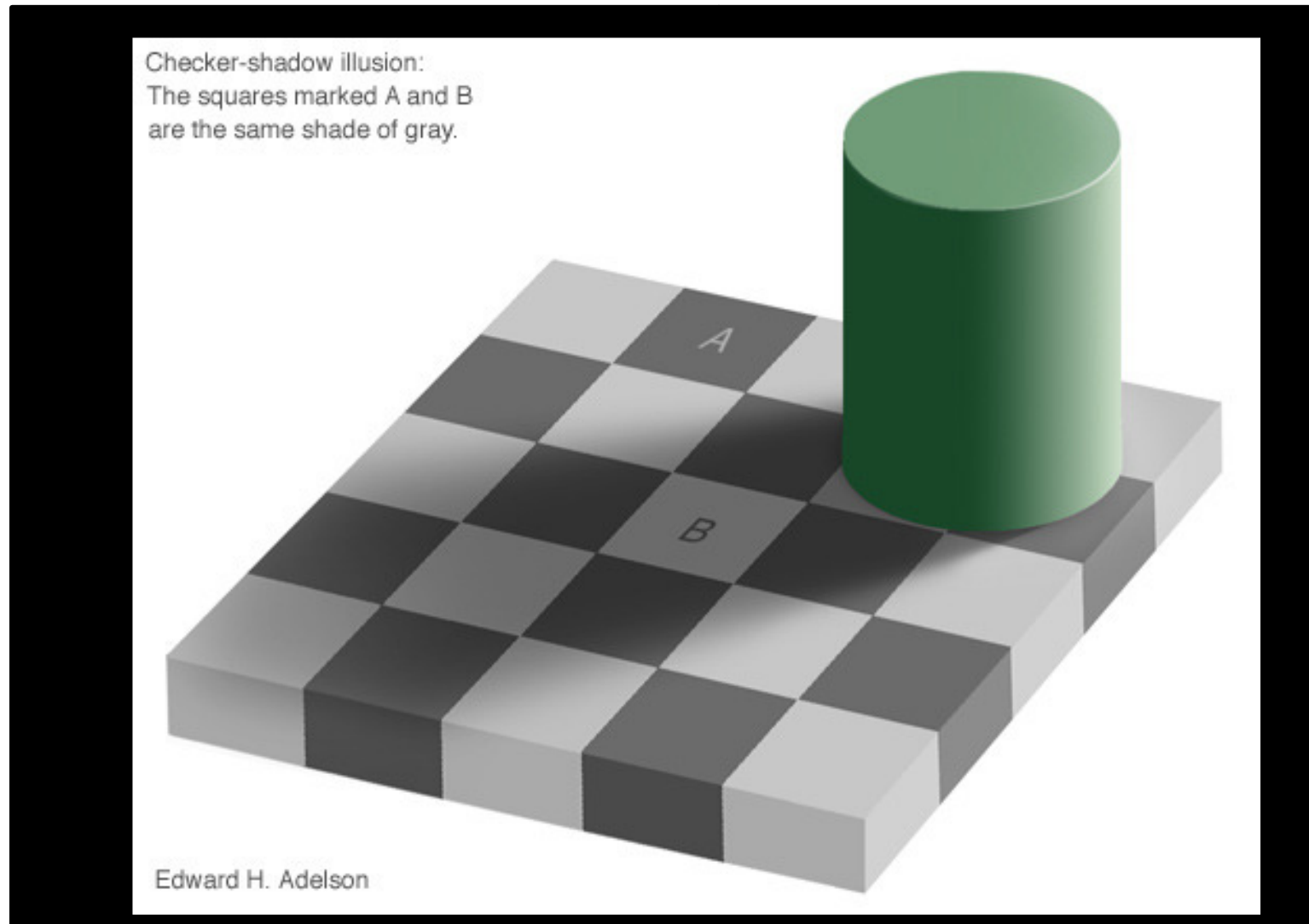
Simultaneous contrast



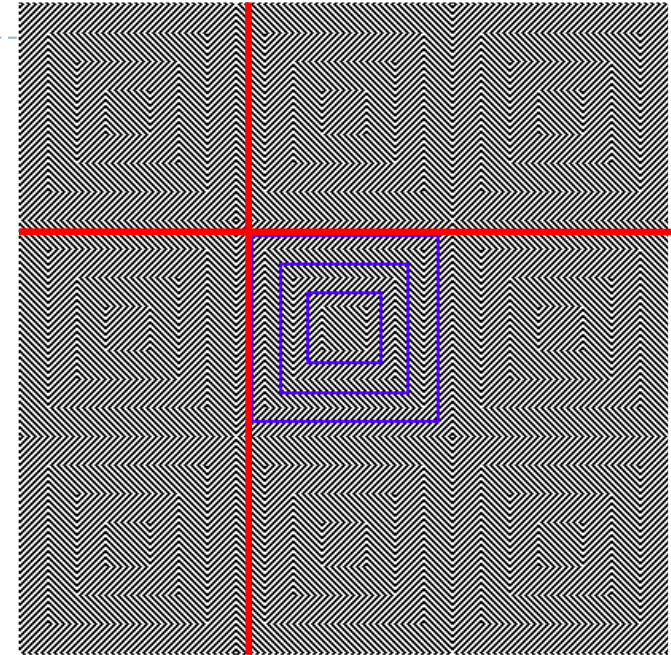
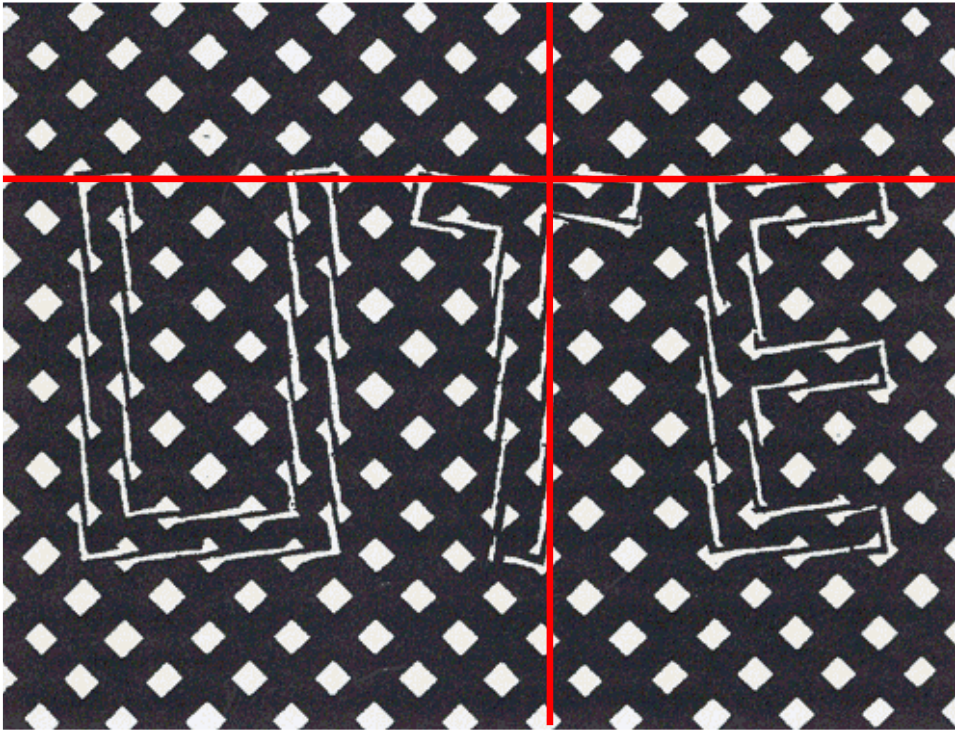
High-Level Contrast Processing



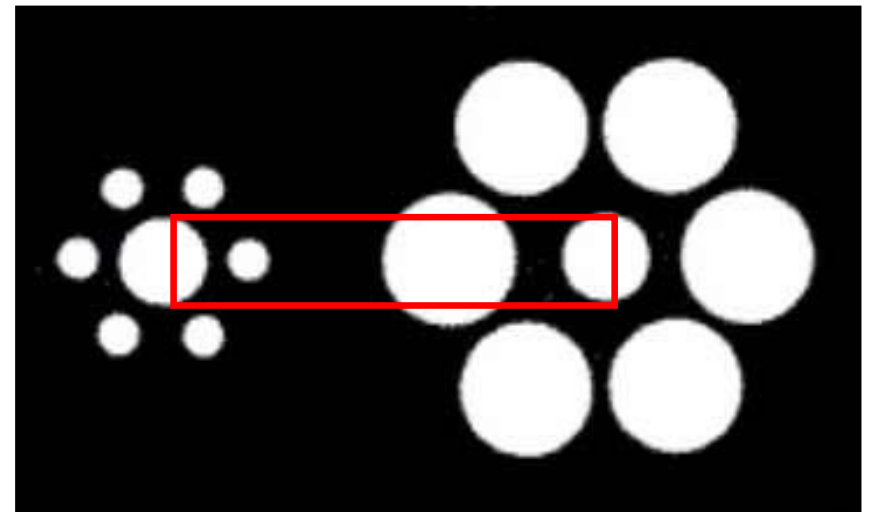
High-Level Contrast Processing



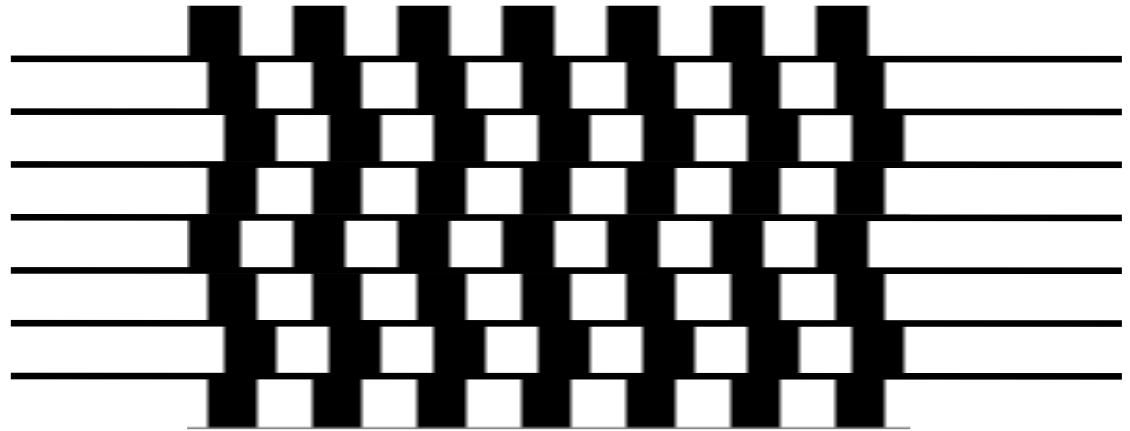
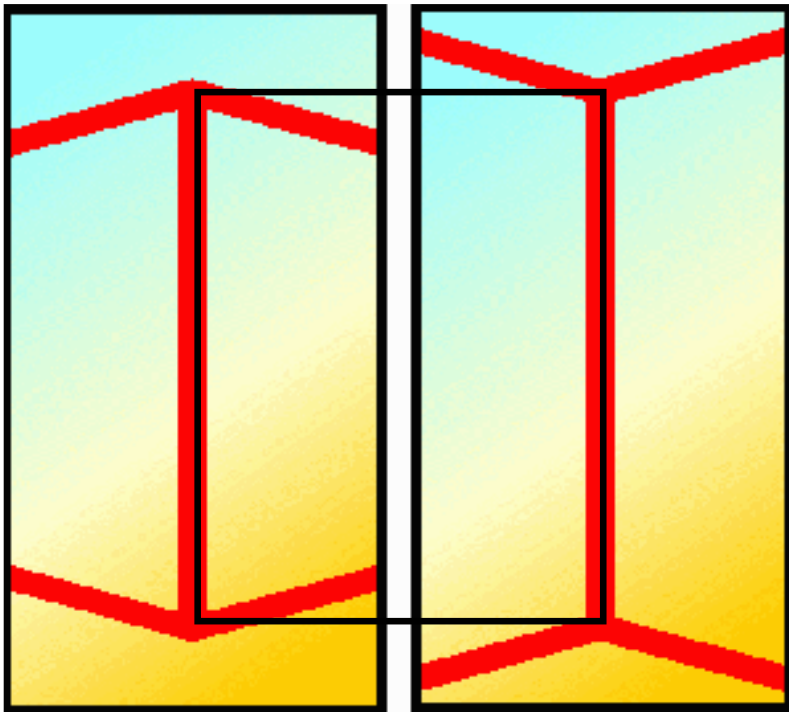
Shape Perception



- Depends on surrounding primitives
 - Directional emphasis
 - Size emphasis



Shape Processing: Geometrical Clues

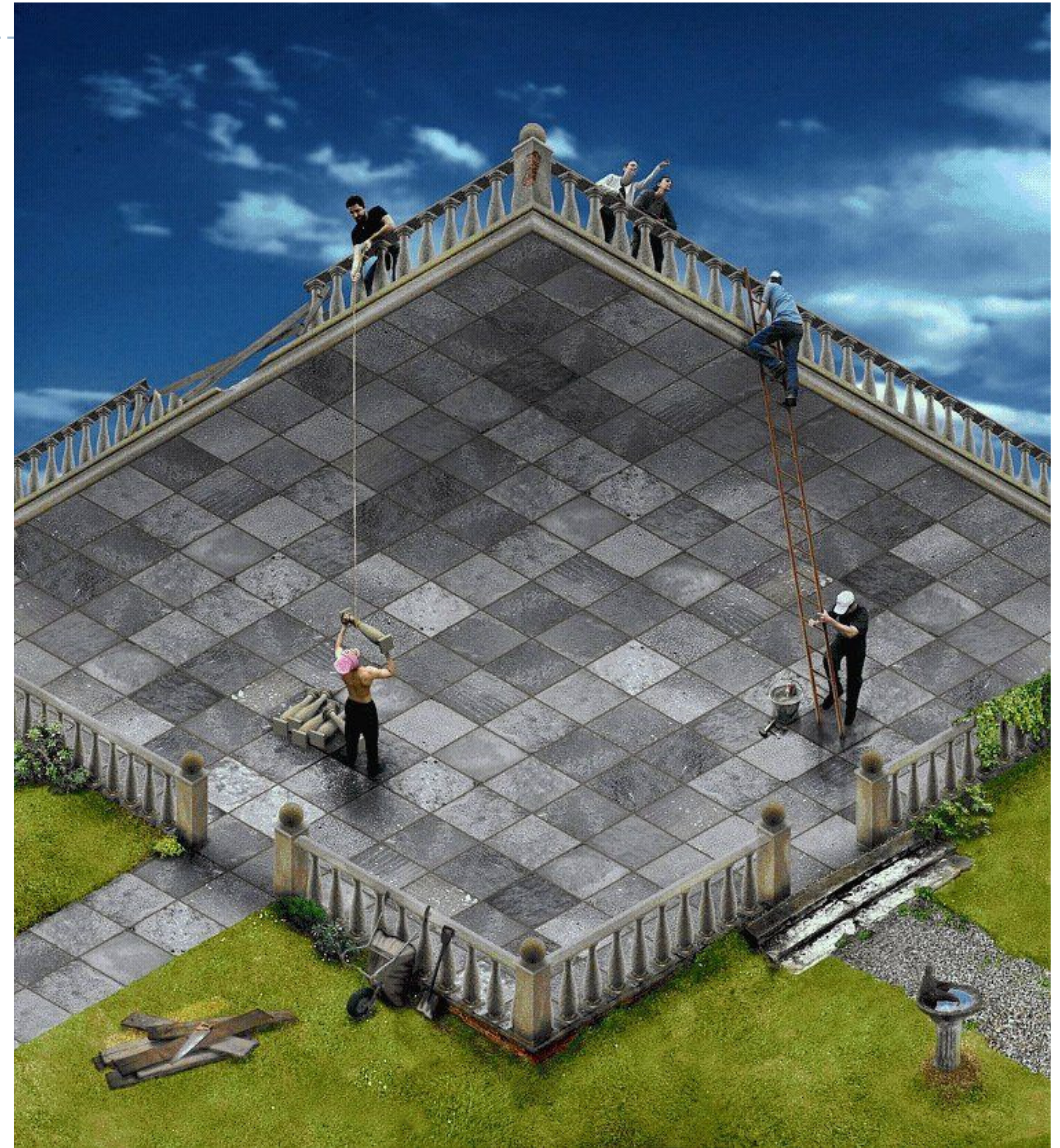
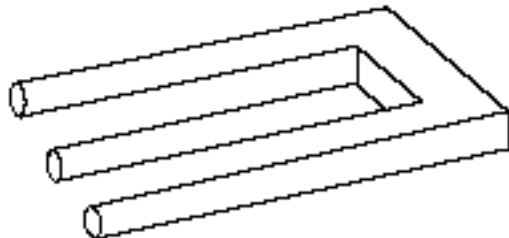
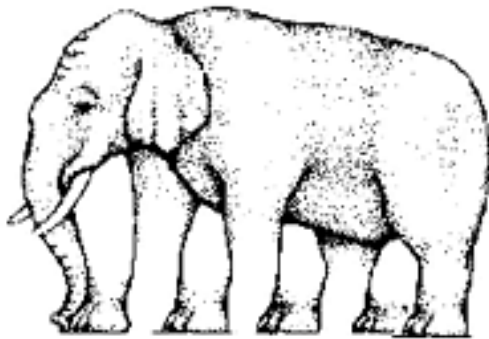


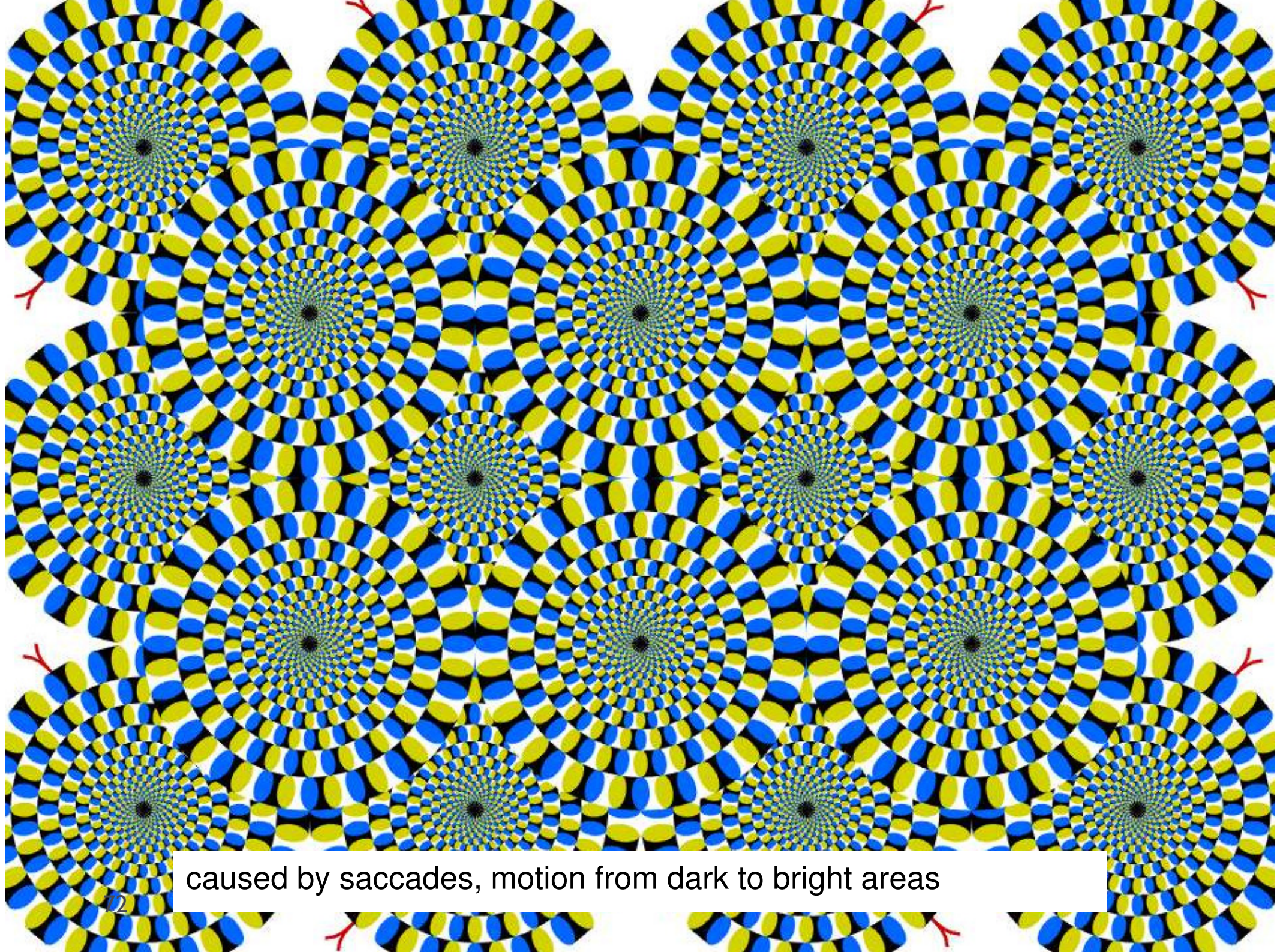
<http://www.panoptikum.net/optischetaeusungen/index.html>

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

Impossible Scenes

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





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