UNIVERSITY OF CAMBRIDGE
COMPUTER LABORATORY

RAINBOW RESEARCH GROUP

Models of early visual perception

Advanced Graphics

Rafal Mantiuk
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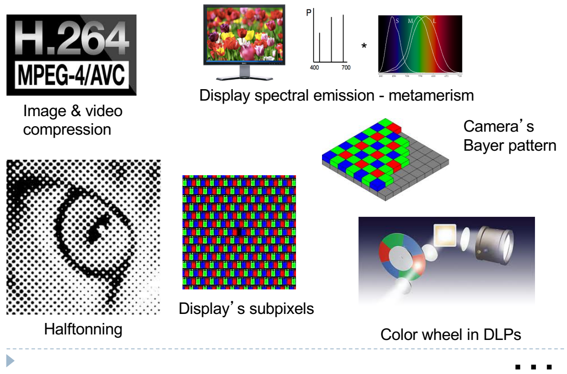
Many technical solutions are motivated by visual perception



Perceived brightness of light

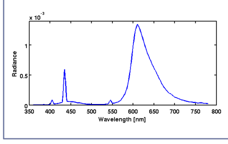
Luminance

- Luminance – how bright the surface will appear regardless of its colour. Units: cd/m^2

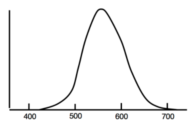
Luminance

$$L_V = \int_0^\infty L(\lambda) \cdot V(\lambda) d\lambda$$

Light spectrum (radiance)



Luminous efficiency function (weighting)



Luminance and Luma

- Luminance
  - Photometric quantity defined by the spectral luminous efficiency function
- L ≈ 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

$$R' = R^{1/\gamma}$$

- Unitless

Steven's power law for brightness

- Stevens (1906-1973) measured the perceived magnitude of physical stimuli
  - Loudness of sound, tastes, small, 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:

Perceived magnitude

$$\varphi(I) = kI^a$$

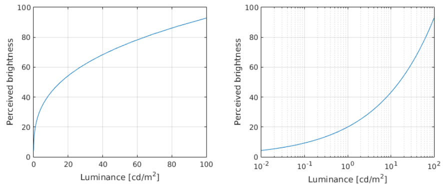
Exponent

Constant

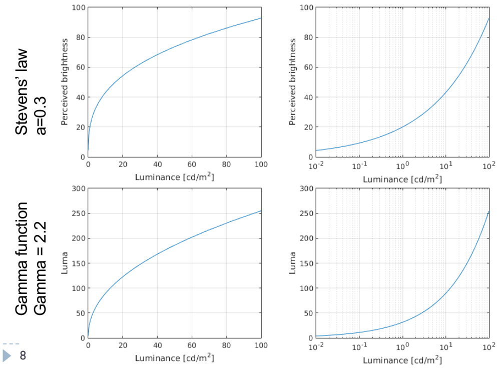
Physical stimulus

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

Steven's law for brightness



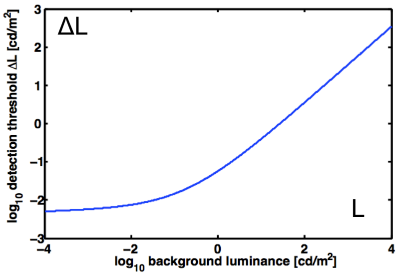
Steven's law vs. Gamma correction

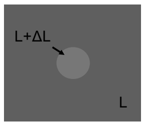


Detection and discrimination

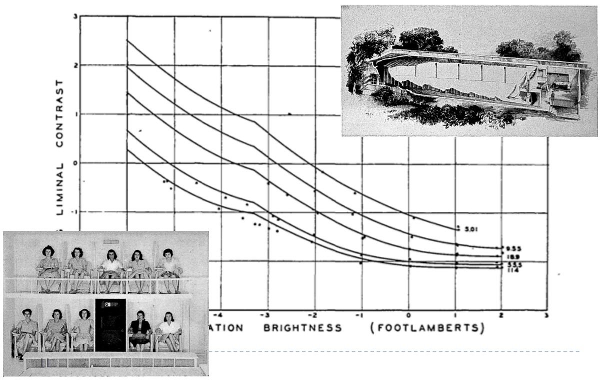
Threshold versus intensity (t.v.i.) function

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

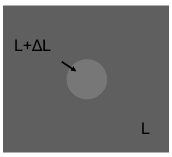


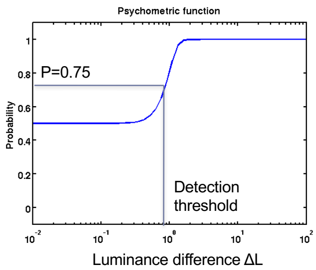


t.v.i. measurements – Blackwell 1946



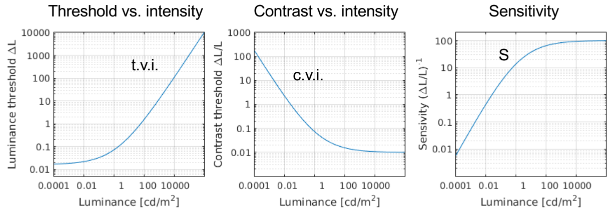
Psychophysics Threshold experiments





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

- The same data, different representation



$\Delta L = L_{disk} - L_{background}$ $\qquad T = \frac{\Delta L}{L}$ $\qquad S = \frac{1}{T} = \frac{L}{\Delta L}$

Sensitivity to luminance

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


Ernst Heinrich Weber
[From wikipedia]

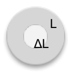
$$\frac{\Delta L}{L} = k$$

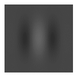
The smallest detectable luminance difference → ΔL

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/m²	1 cd/m²
1 cd/m²	0.01 cd/m²

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

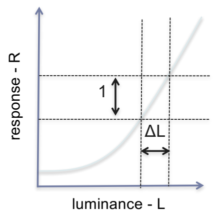
How to make luminance (more) perceptually uniform?

- Using "Fechnerian" integration

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

Derivative of response: $\frac{dR}{dl}(L)$

Detection threshold: $\Delta L(L)$



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

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

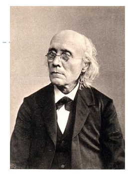
- the response of the visual system to light is:

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

Fechner law

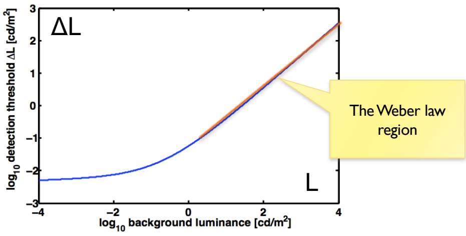
$$R(L) = a \ln(L)$$

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


Gustav Fechner
[From Wikipedia]

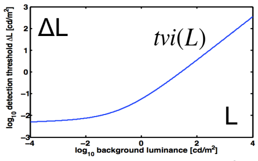
But…the Fechner law does not hold for the full luminance range

- 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:

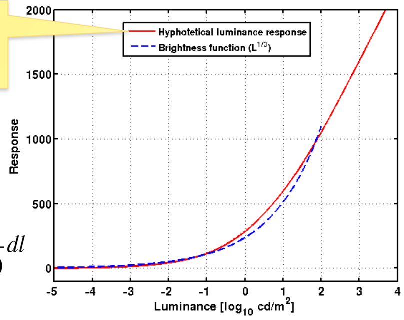


- we can get more accurate estimate of the "response":

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

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)

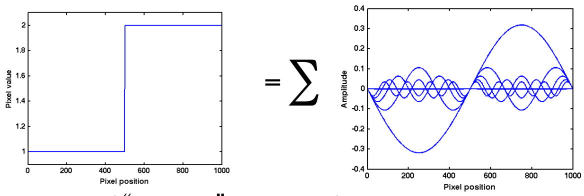
- DICOM grayscale function
  - Function used to encode signal for medial monitors
  - 10-bit JND-scaled (just noticeable difference)
  - Equal visibility of gray levels
- HDMI 2.0a (HDR10)
  - PQ (Perceptual Quantizer) encoding
  - Dolby Vision
  - To encode pixels for high dynamic range images and video

DOLBY VISION
The Future of Vision

Spatial contrast sensitivity

Fourier analysis

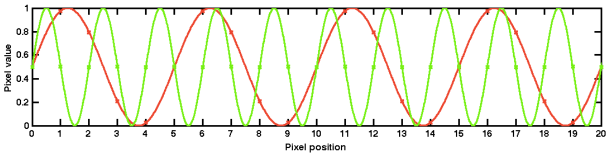
- Every N-dimensional function (including images) can be represented as a sum of sinusoidal waves of different frequency and phase



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

Spatial frequency in images

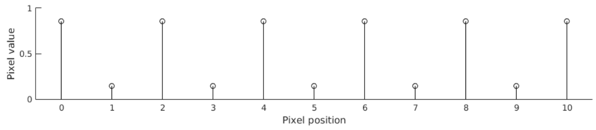
- Image space units: cycles per sample (or cycles per pixel)



  - 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

- What is the highest frequency that can be reconstructed for a given sampling density?
  - 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

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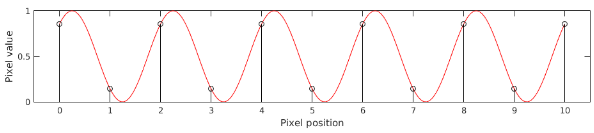

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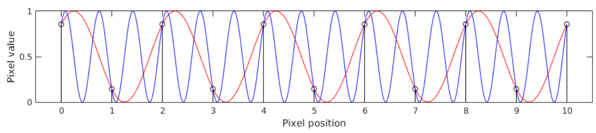

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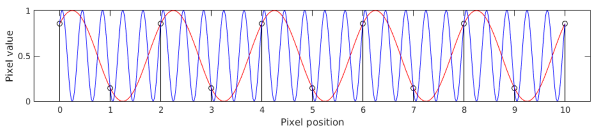
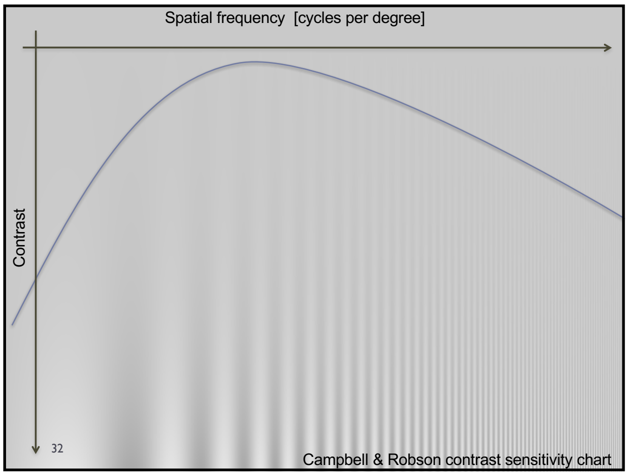


  - Any number of sinusoids can be fitted to this set of samples
  - It is possible to fit an infinite number of sinusoids if we allow infinitely high frequency

Nyquist frequency / aliasing

- 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



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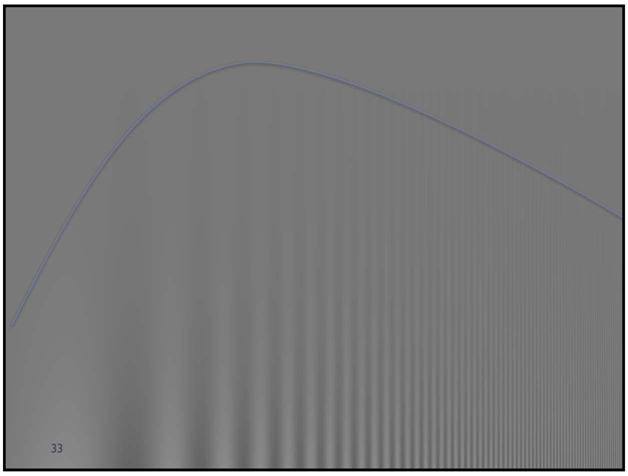

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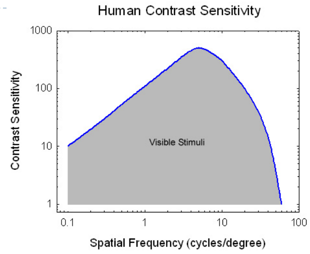
Contrast Sensitivity

- Sensitivity:
  1 / threshold contrast
- Contrast = ΔL/L
- Maximum sensitivity 2-5 cycles/degree
  - Decrease toward low frequencies: lateral inhibition
  - Decrease toward high frequencies
  - Upper limit: 60-70 cycles/degree



Rationale: if we were sensitive to low frequencies, the vision would be affected by changes of illumination. There are physical limitations to the perception of high frequencies.

www.psychology.psych.ndsu.nodak.edu

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Implications of CSF

- As objects get further away, they get smaller; spatial frequencies get higher
  - At some point we cannot see the details
  - That is the upper limit of the CSF (60-70 cpd)
- When we get to close to low frequency patterns, they seem to be constant
  - The background of this slide contains a smooth gradient
  - It is well visible when you look at it from a normal viewing distance
  - Now enlarge the slide to full screen and move your head very close
  - The gradient should disappear

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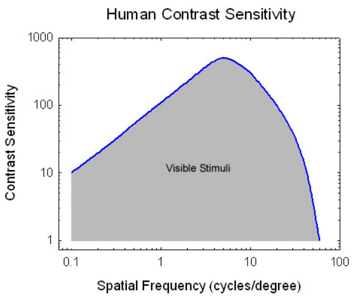
Explaining the effects with CSF

- Can you explain the effects described on the previous slide using the CSF plot?



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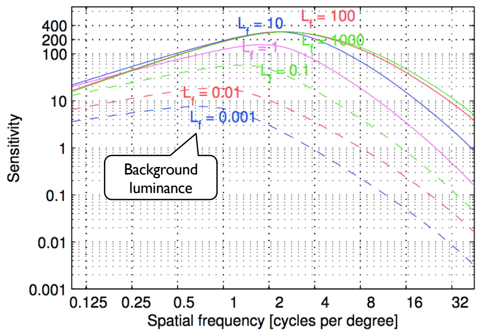
CSF as a function of spatial frequency



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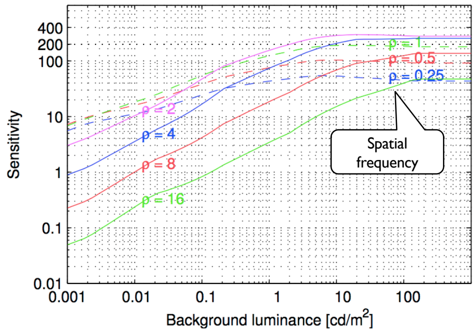
CSF as a function of background luminance



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Contrast constancy

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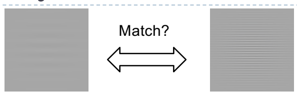
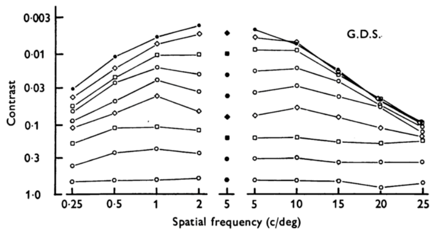
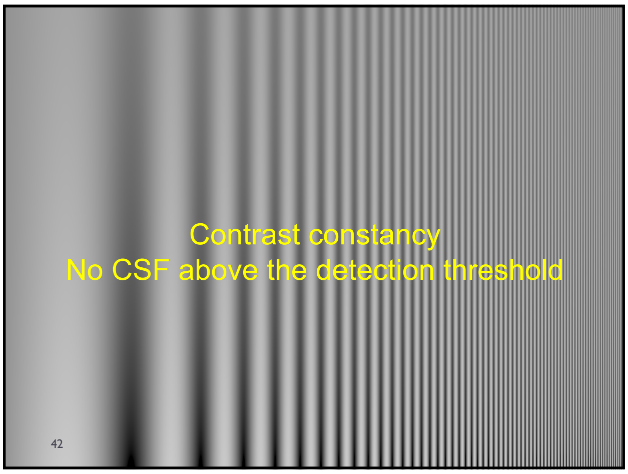
Contrast constancy

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



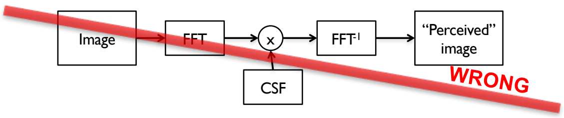


41 From: Georgeson and Sullivan. 1975. J. Phsysio.



Contrast constancy

- For high (supra-threshold) contrast, the perceived magnitude of contrast does not change with spatial frequency
- The CSF gets "flat" above the detection threshold
- A common mistake - using CSF as a linear filter:



  - why CSF cannot be used as a linear filter?

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Multi-resolution models

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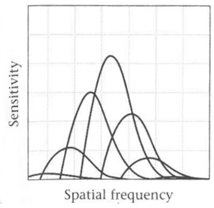
Spatial-frequency selective channels

- 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

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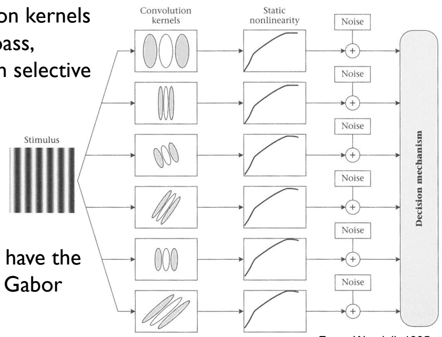
Multi-resolution visual model

- Convolution kernels are band-pass, orientation selective filters
- The filters have the shape of a Gabor function



From: Wandell, 1995

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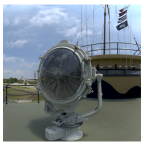
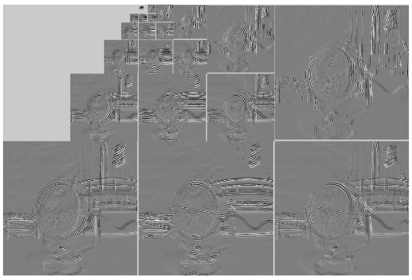
Multi-scale decomposition



Steerable pyramid decomposition



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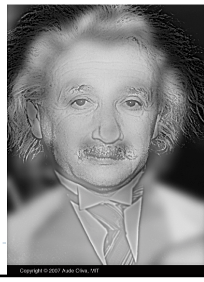
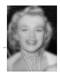
Applications of multi-scale models

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

JPEG 2000





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

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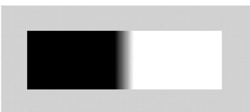
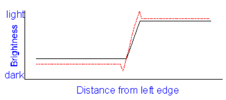
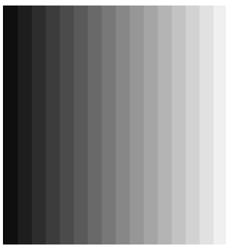
Mach Bands – evidence for band-pass visual processing

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







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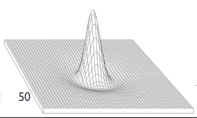
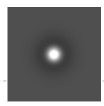
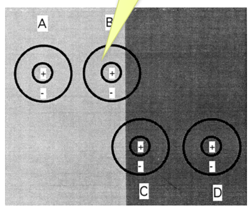
Centre-surround (Lateral Inhibition)

- "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)







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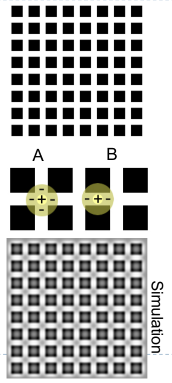
Centre-surround: Hermann Grid

- 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 ?



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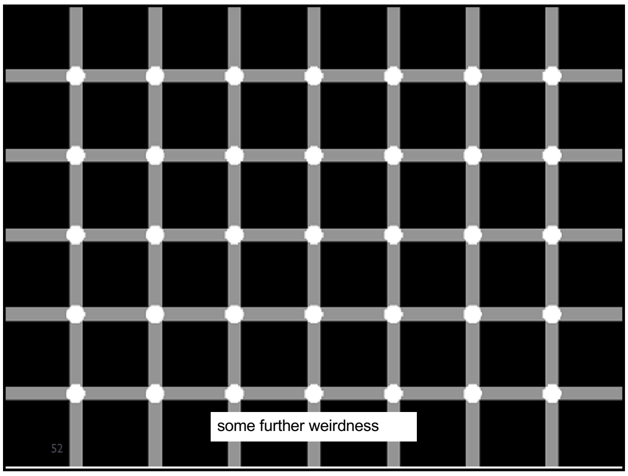

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Light and dark adaptation

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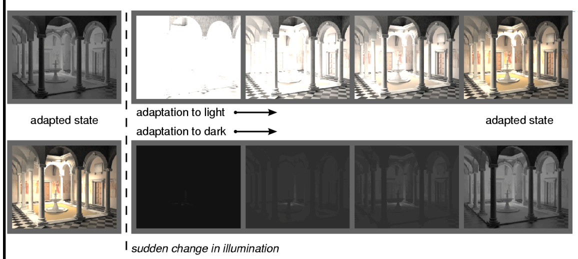
Light and dark adaptation



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

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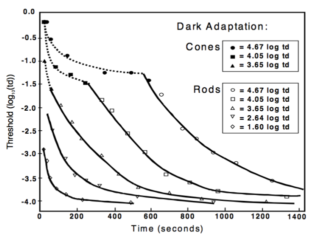
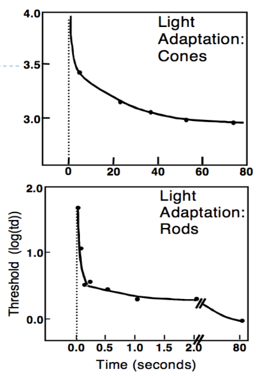
Time-course of adaptation



Bright -> Dark



Dark -> Bright

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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)

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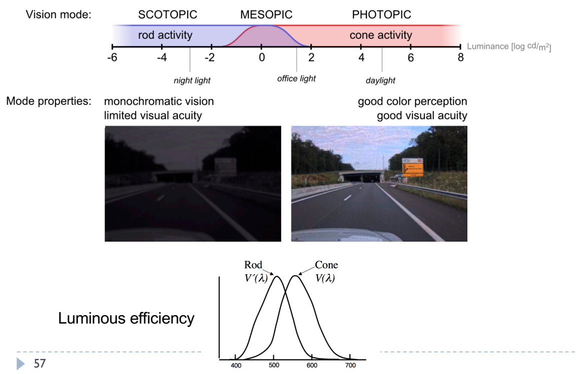
Night and daylight vision



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Opponent colours and spatial colour vision

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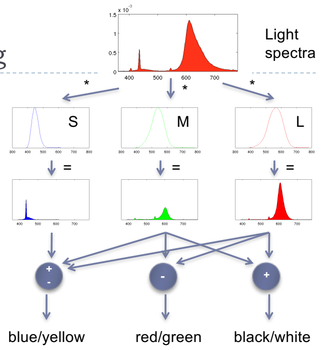
Colour processing

- Light is sensed by L, M and S, cones
  - Each cone type is sensitive to different wavelengths
- Responses from L, M and S cones are combined into three opponent pathways
  - achromatic (black/white) pathway – luminance
  - 2 colour opponent pathways
- Rationale: improve coding efficiency for natural scenes



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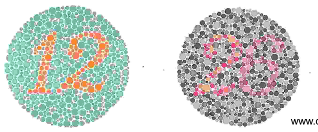
Colour perception

- Di-chromaticity (dogs, cats)
  - Yellow & blue-violet
  - Green, orange, red indistinguishable
- Tri-chromaticity (humans, monkeys)
  - Red, green, blue
  - Colour-blindness
    - Most often men, green-red colour-blindness

www.lam.mus.ca.us/cats/color/



www.colorcube.com/illusions/clrblnd.html

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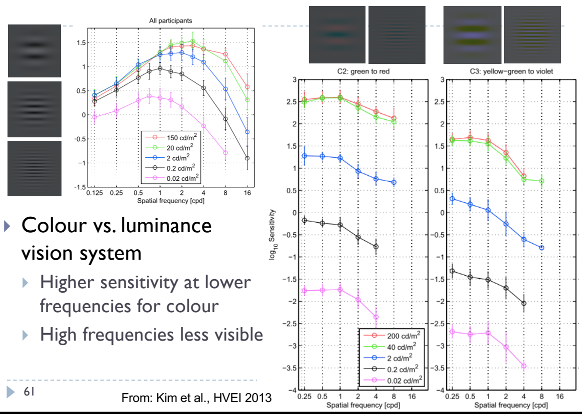
Colour Contrast Sensitivity



- Colour vs. luminance vision system
  - Higher sensitivity at lower frequencies for colour
  - High frequencies less visible

From: Kim et al., HVEI 2013

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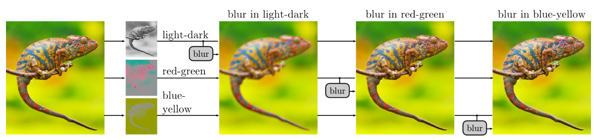
Visibility of blur



- 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)

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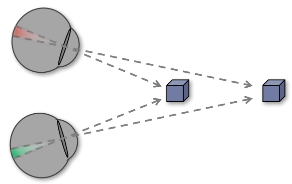
Depth perception

The slides in this section are the courtesy of Piotr Didyk (http://people.mpi-inf.mpg.de/~pdidyk/)

Depth perception

We see depth due to depth cues.

Stereoscopic depth cues:
binocular disparity

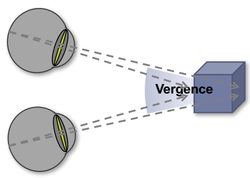


Depth perception

We see depth due to depth cues.

Stereoscopic depth cues:
binocular disparity

Ocular depth cues:
accommodation, vergence



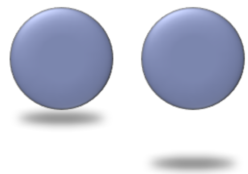
Depth perception

We see depth due to depth cues.

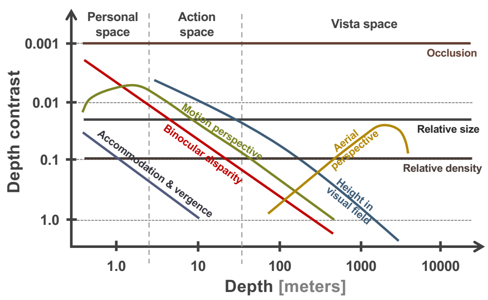
Stereoscopic depth cues:
binocular disparity

Ocular depth cues:
accommodation, vergence

Pictorial depth cues:
occlusion, size, shadows…



Cues sensitivity



"Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth" by Cutting and Vishton [1995]

Depth perception

We see depth due to depth cues.

Stereoscopic depth cues:
binocular disparity

Ocular depth cues:
accommodation, vergence

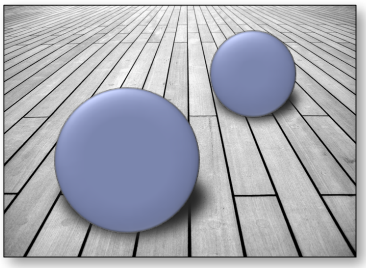
Pictorial depth cues:
occlusion, size, shadows…

Challenge:
Consistency is required!

Simple conflict example

Present cues:

- Size
- Shadows
- Perspective
- **Occlusion**



Disparity & occlusion conflict

Objects in front

Disparity & occlusion conflict

Disparity & occlusion conflict

Depth perception

We see depth due to depth cues.

Stereoscopic depth cues:
binocular disparity

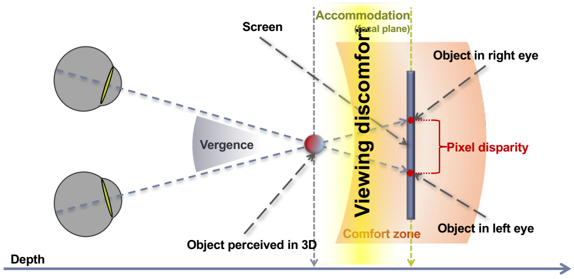
Ocular depth cues:
accommodation, vergence

⇨ **Require 3D space**
We cheat our Human Visual System!

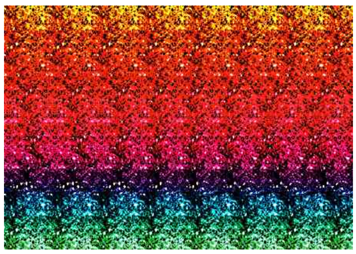
Pictorial depth cues:
occlusion, size, shadows…

⇨ **Reproducible on a flat displays**

Cheating our HVS



Single Image Random Dot Stereograms



- Fight the vergence vs. accommodation conflict to see the hidden image

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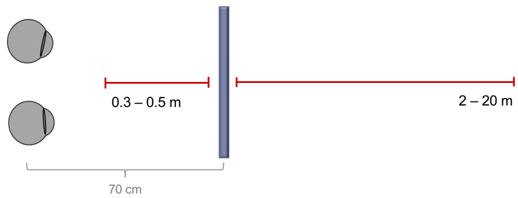
Viewing discomfort

Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition

Simple scene



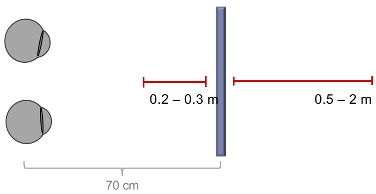
"Controlling Perceived Depth in Stereoscopic Images" by Jones et al. 2001

Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition

Simple scene, user allowed to look away from screen



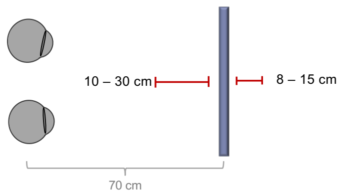
"Controlling Perceived Depth in Stereoscopic Images" by Jones et al. 2001

Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition

Difficult scene



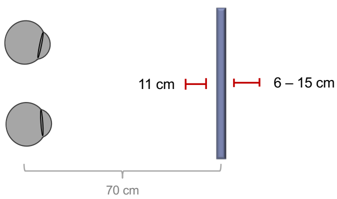
"Controlling Perceived Depth in Stereoscopic Images" by Jones et al. 2001

Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition

Difficult scene, user allowed to look away from screen



"Controlling Perceived Depth in Stereoscopic Images" by Jones et al. 2001

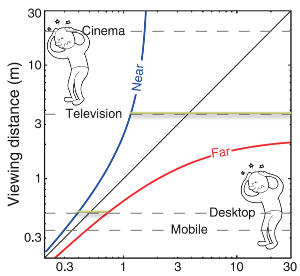
Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition
- Screen distance

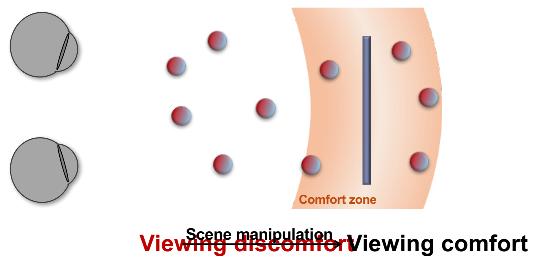
Other factors:

- Distance between eyes
- Depth of field
- Temporal coherence



"The zone of comfort: Predicting visual discomfort with stereo displays" by Shibata et al. 201

Depth manipulation



High(er) level vision

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Simultaneous contrast

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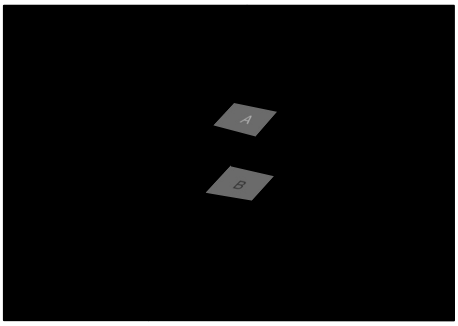
High-Level Contrast Processing



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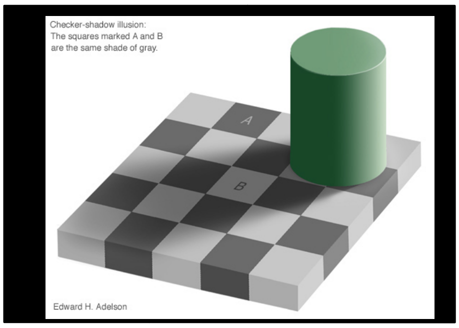
High-Level Contrast Processing



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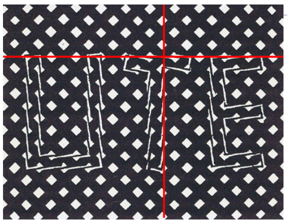
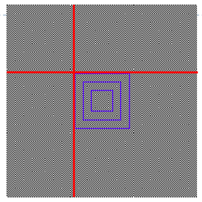
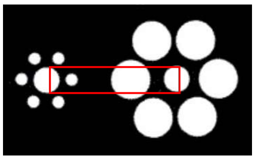
Shape Perception



- Depends on surrounding primitives
  - Directional emphasis
  - Size emphasis





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

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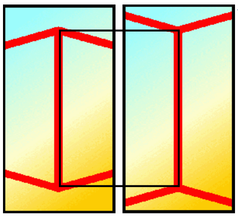
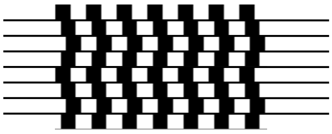
Shape Processing: Geometrical Clues





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

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

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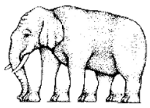
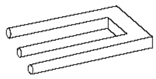
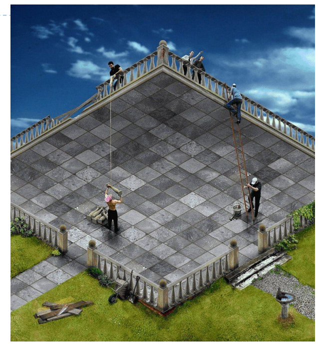
Impossible Scenes

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







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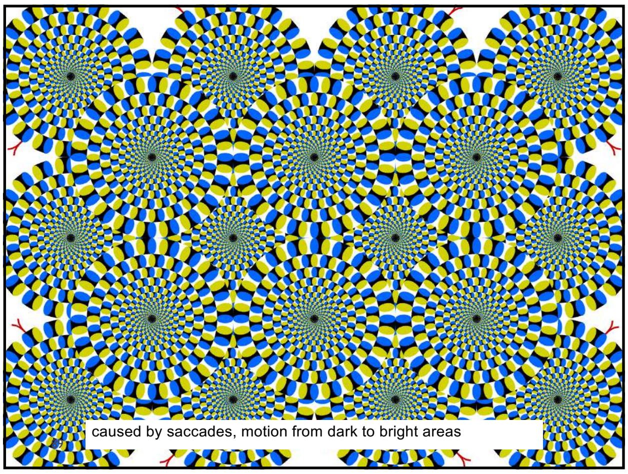

caused by saccades, motion from dark to bright areas

Law of closure

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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

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