

# Advanced Image Processing

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## Part I:

### Human Visual System

S. Voloshynovskiy



# Recommended books

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- B.A. Wandell, Foundations of Vision, Sinauer Associates, Inc., 1995.
- A. K. Jain, Fundamentals of Digital Image Processing, Prentice-Hall, 1989.

# Roadmap:

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1. Introduction
2. Perceived information attributes (light, luminance, brightness, contrast)
3. Optical properties of the Human Visual System (HVS):  
    Point Spread Function and Modulation Transfer Function
3. Masking
4. Image quality (fidelity) criteria
5. Conclusions

# Introduction

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Why is it important to know the features of the Human Visual System (HVS)?

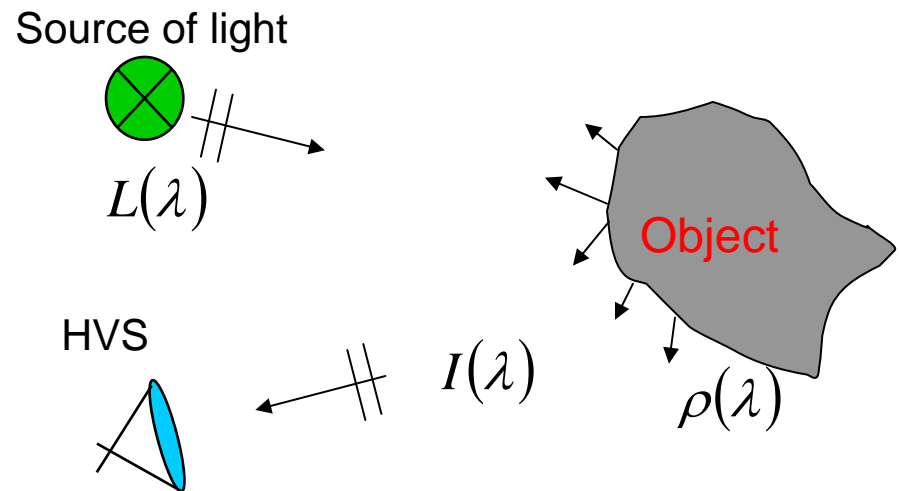
1. To develop measures of image fidelity and quality.
2. To design the algorithms matched with these measures.
3. To exploit the knowledge of the HVS for efficient compression, denoising, restoration and watermarking.

# Perceived information attributes

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**Light** is the electromagnetic radiation that stimulates our visual response.

Visible range of human eye:  
 $350 \text{ nm} < \text{wavelength} > 780 \text{ nm}$   
 $\lambda$



Light received from the object:

$$I(\lambda) = \rho(\lambda) L(\lambda)$$

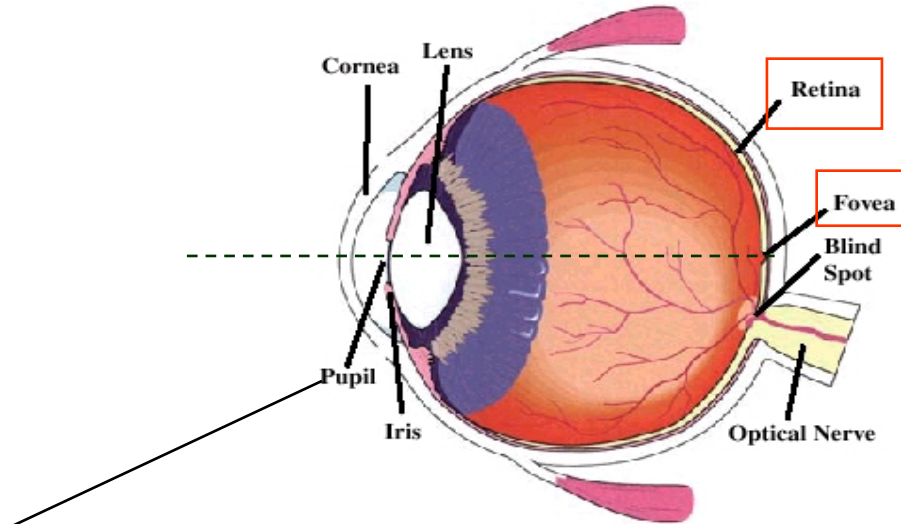
Reflectivity      Incident light

# The Human Eye

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Retina contains two types of photoreceptors :

- 100 millions of *rods* (dark environment)
- 6.5 millions of *cones* (well-lighted environment, high resolution and color vision)



Cones are packed in Fovea.  
Rods are distributed over all  
Retina.

Pupil acts as small imaging aperture (size is varying from 2 to 8 mm).

Lens determines the aperture focusing. Iris is the muscle that controls the pupil size.

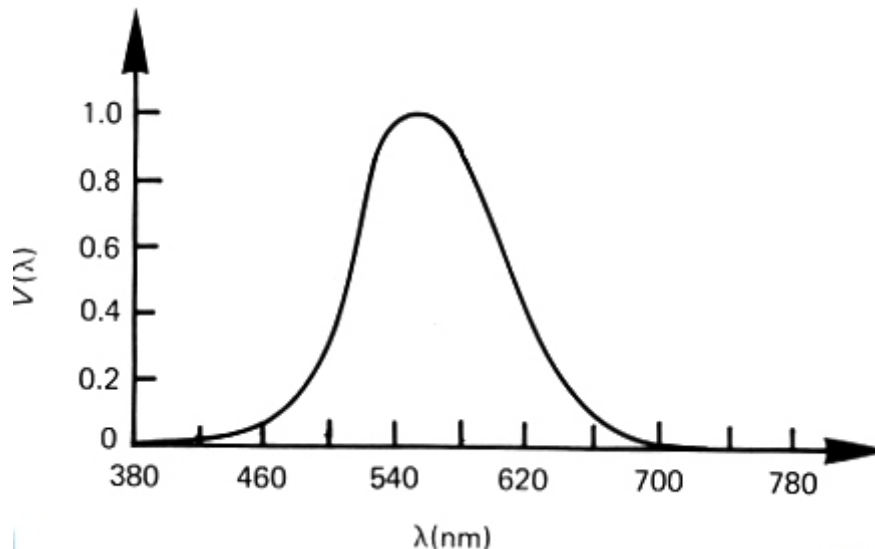
# Perceived information: Luminance and Brightness

**Luminance** (or intensity) :

$$f(i, j) = \int_0^{\infty} I(i, j, \lambda) V(\lambda) d\lambda$$

Spatial object light distribution.

relative luminous efficiency  
function of the HVS (describes  
the sensitivity of the HVS to  
different wavelength)



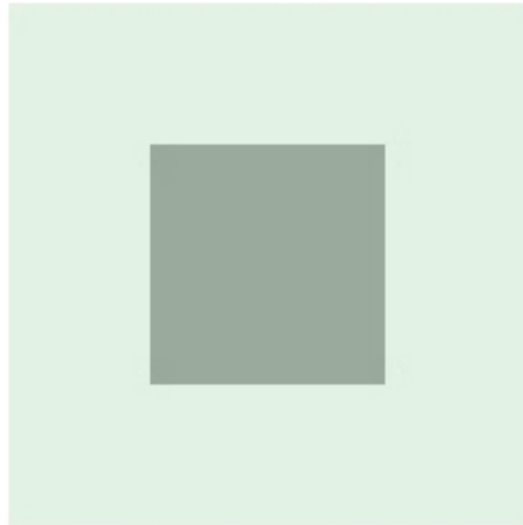
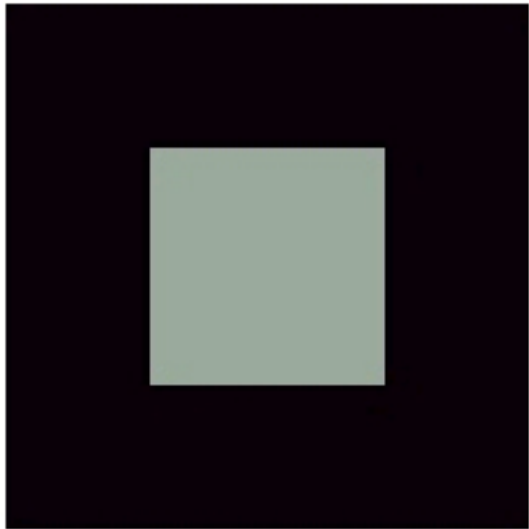
The luminance of the object is independent  
of the luminance of the surrounding objects.

The **brightness** of an object is **the perceived luminance** and depends on the luminance of  
the surround.

# Perceived information attributes

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**Brightness** is the perceived luminance. It depends on luminance of the surround:



Small squares in the middle have equal luminances but do not appear equally bright.

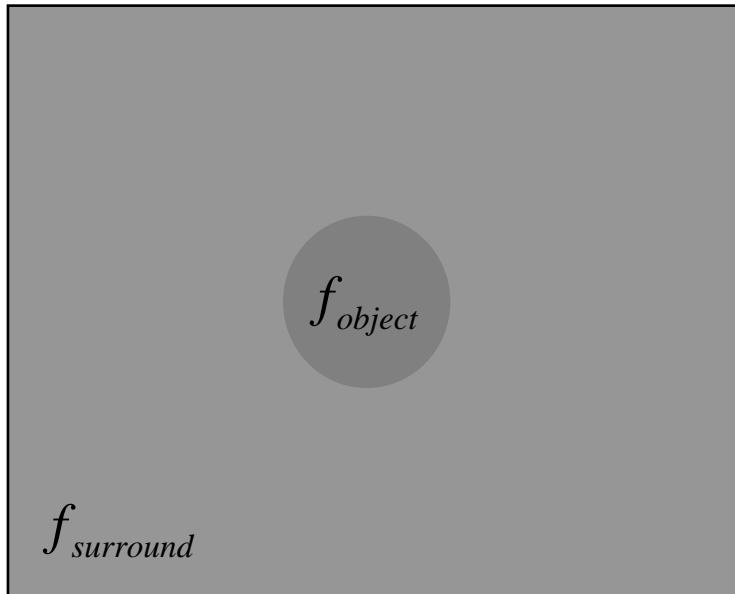
The human perception is sensitive to luminance contrast rather than the absolute luminance values themselves.



# Visibility Threshold: Weber law

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Can you see the circle?



- The HVS can perceive the small difference in luminance.
- However, the minimum difference that can be perceived depends on the surround luminance.
- This dependence is known as **contrast sensitivity**.

$$\text{Weber's law: } \frac{|f_{\text{surround}} - f_{\text{object}}|}{f_{\text{object}}} = \text{constant}$$

If the luminance of an object is just noticeable difference from the luminance of its surround, then their ratio is constant.

# Perceived information attributes

- Let:  $f_{object} = f$  and  $f_{surround} = f + \Delta f$  — Just noticeable difference

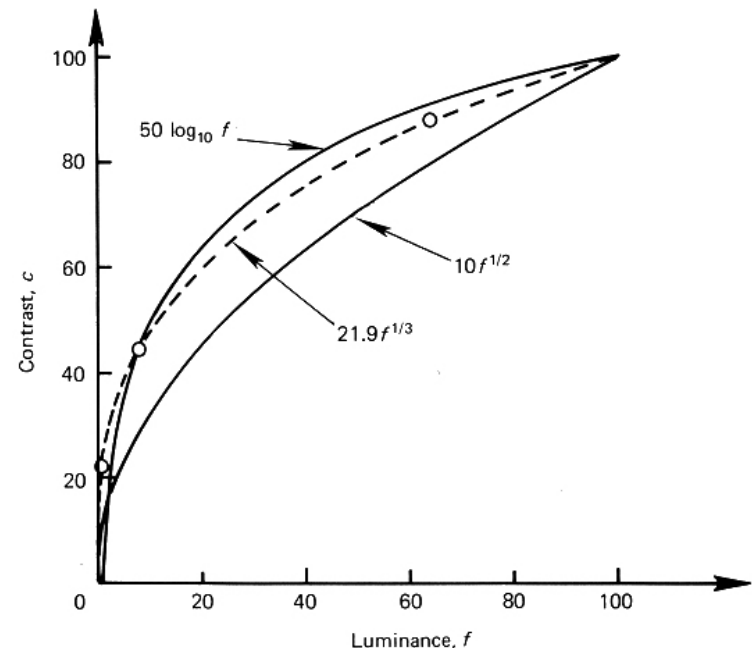
$$\frac{\Delta f}{f} \cong d(\log f) = \Delta c \quad (\text{constant}) \approx 0.02$$

## Luminance-to-Contrast ( $c$ ) models:

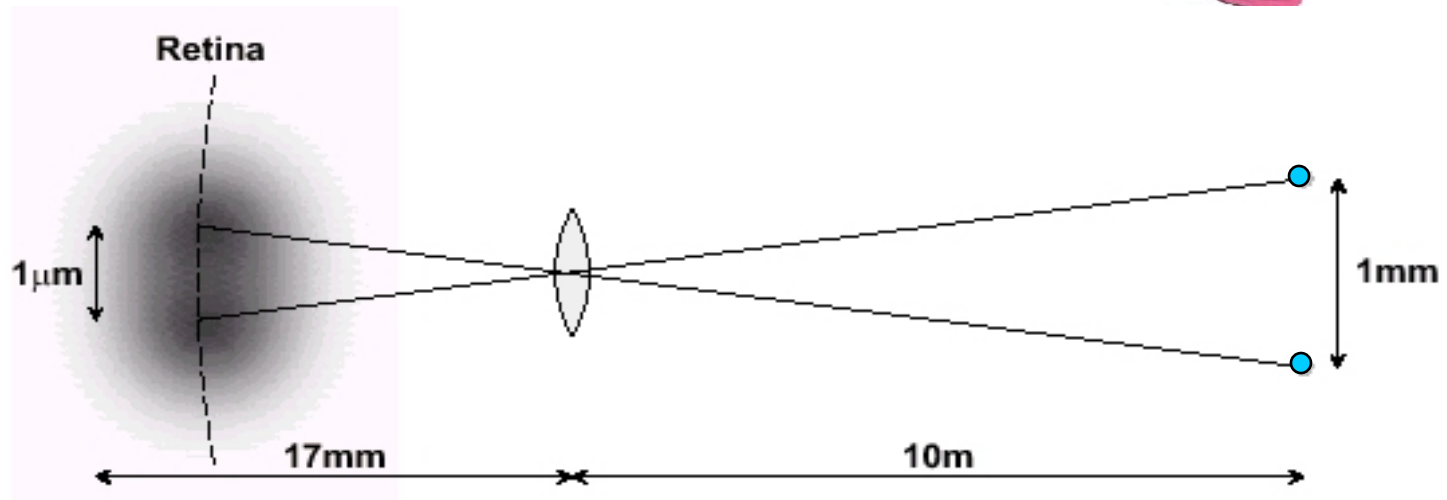
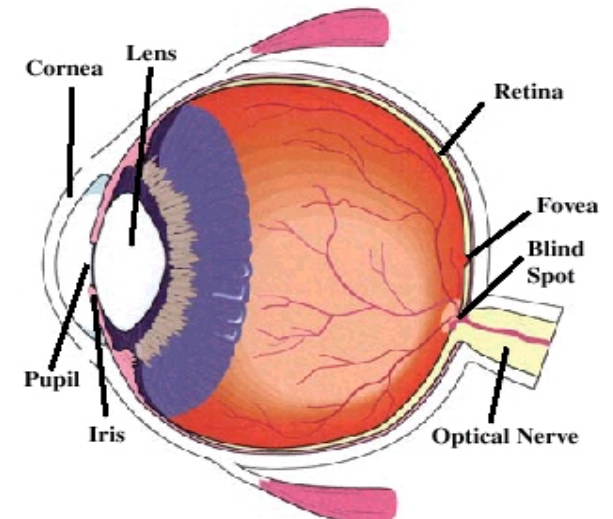
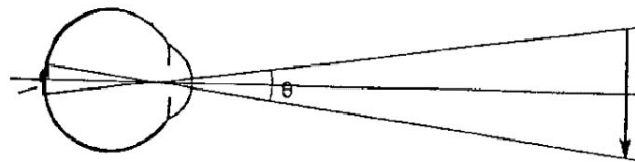
- Logarithmic law:  $c = 50 \log_{10} f$ ,  $1 \leq f \leq 100$

- Power law:  $c = \alpha_n f^{1/n}$ ,  $n = 2, 3, \dots$   
 $\alpha_2 = 10$ ,  $\alpha_3 = 21.9$

- Background ratio:  $c = \frac{f(f_b + 100)}{f_b + f}$   
 $f_b$  — background luminance



# Optical properties of the HVS



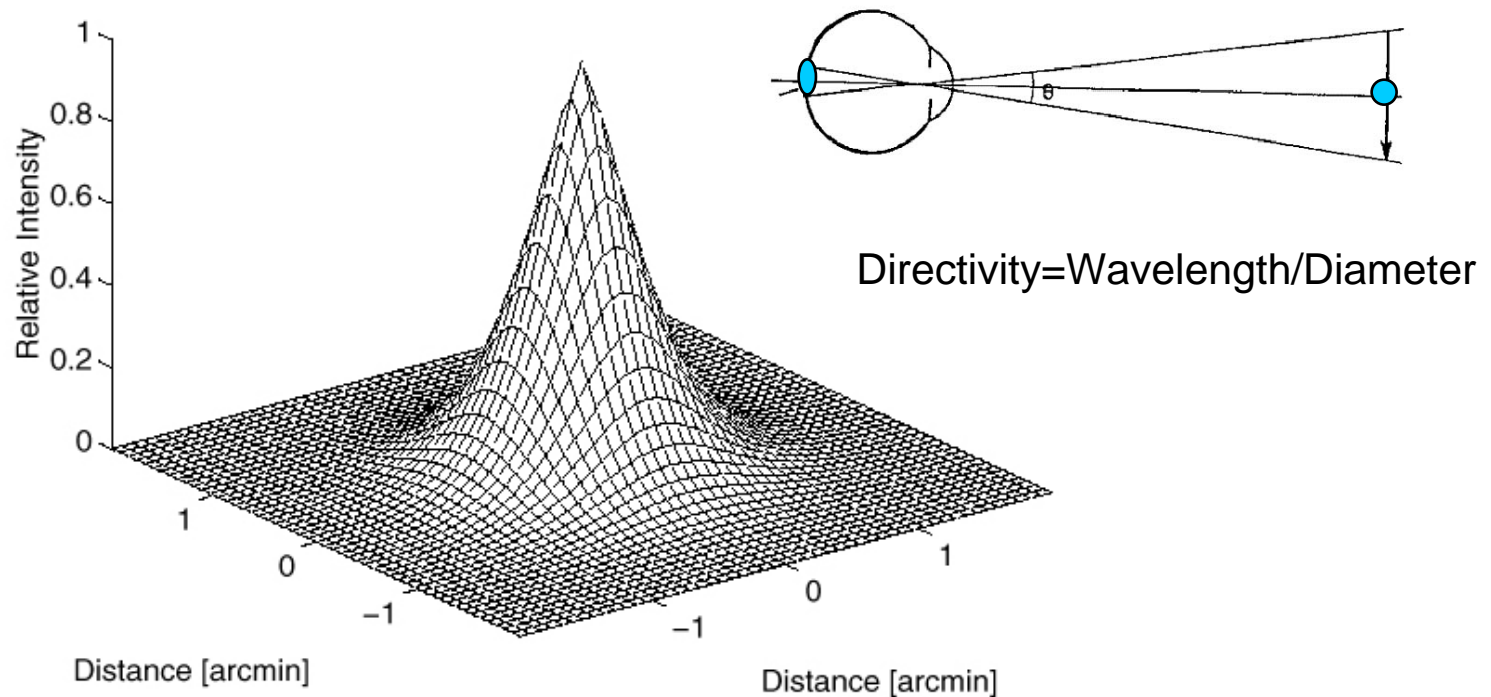
# Optical properties of the human eye

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- Deviations from ideal perspective projection due to
  - Aperture of the eye
  - Focus errors (spherical aberration)
  - Chromatic aberration
  - Dispersion
- Effects can be summarized by a 2D convolution with the optical point-spread function (PSF).
- Instead of a PSF, an optical line-spread function (LSF) is often given, which can be measured more easily.

# Optical properties of the human eye: the PSF

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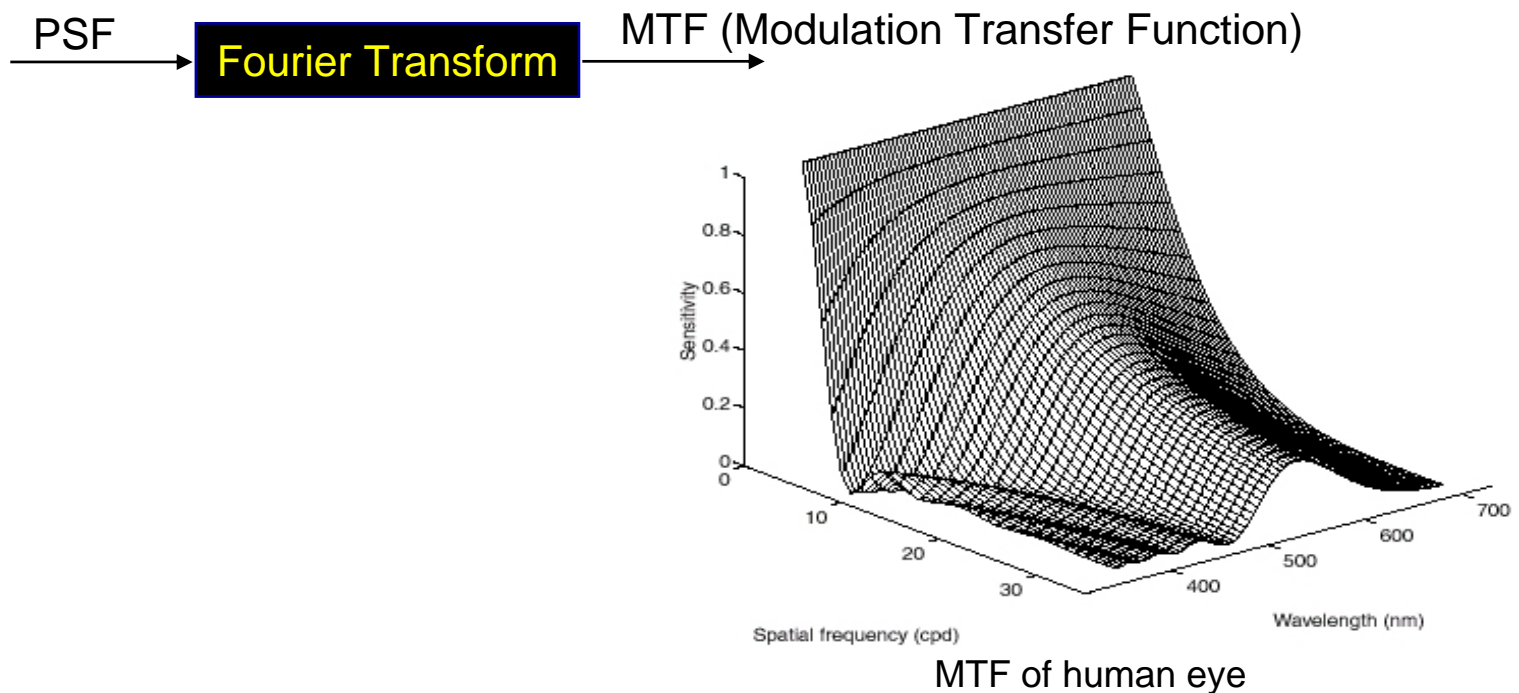
Because the cornea is not perfectly symmetric the optical properties of the eye are not shift invariant.

# Optical properties of the human eye: the PSF

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Additionally, it is difficult to focus the eye for all wavelengths simultaneously (it is known as **chromatic aberration**).

Therefore, the PSF changes with wavelength.

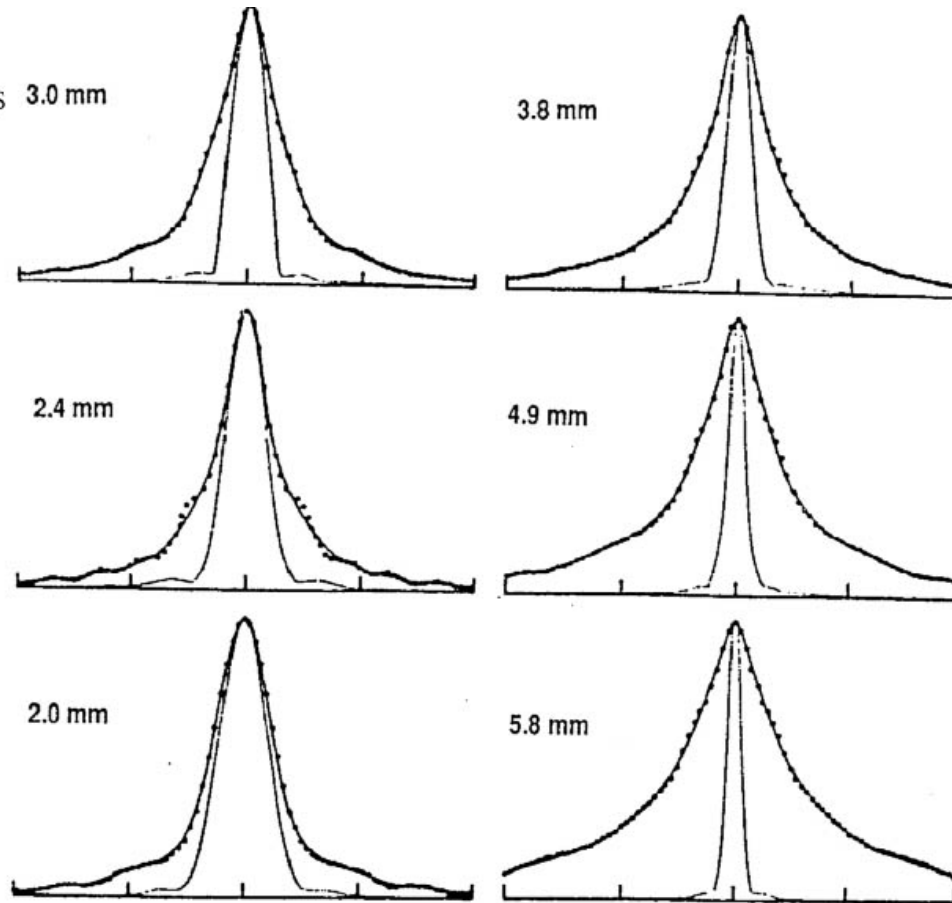


# Optical LSF of the human eye

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--- LSF measured for  
different pupil diameters  
(Campbell+Gubisch)

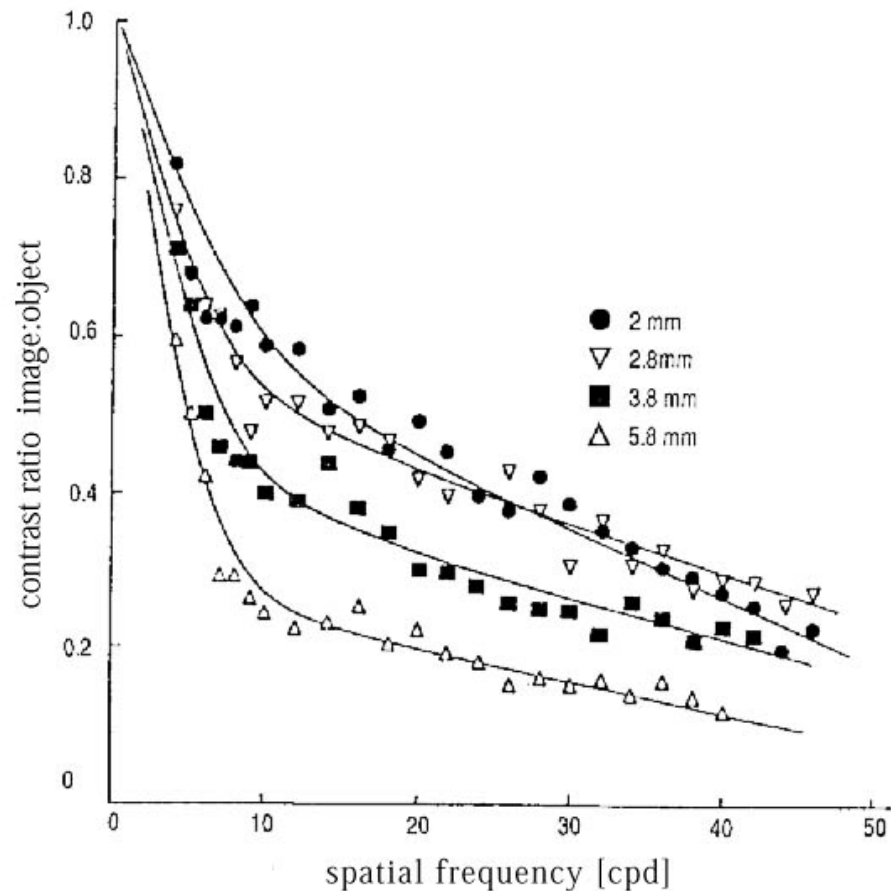
— LSF calculated from  
eye aperture  
(due to diffraction)



# Optical Modulation Transfer Function (MTF) of human eye

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- MTF is measured directly with sinewave gratings.
- The optical modulation transfer function (MTF) can be interpreted as Fourier transform of the optical LSF.





# Practical Estimation of the MTF

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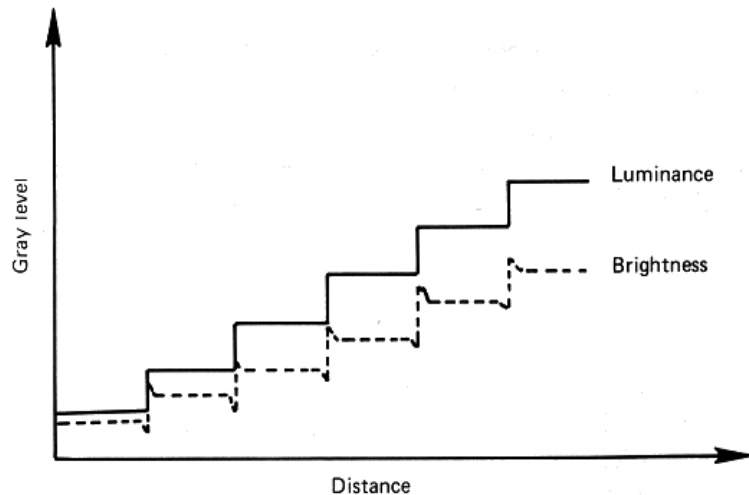
The MTF (or the impulse response of the HVS) can be estimated:

- directly in the spatial domain using a Mach band effect;
- using spatial sinusoidal grating of varying contrast and spatial frequencies.

# Mach Bands

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Mach bands – the measure of visual system in spatial domain.

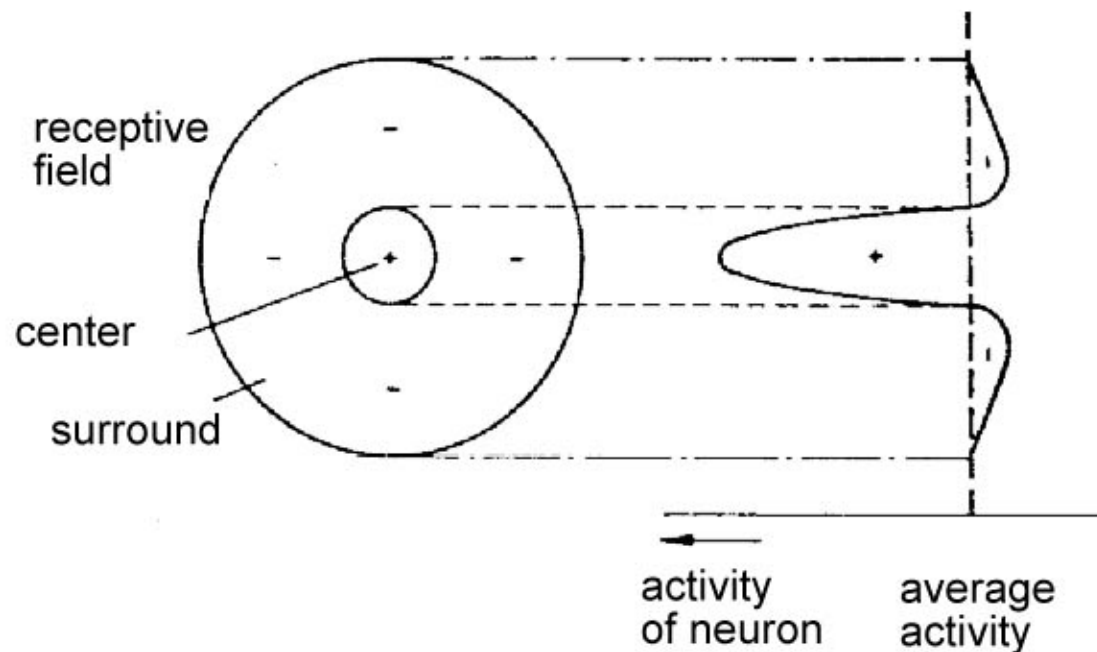


The bars have constant luminance.

However, the apparent brightness is not uniform along the width of the bar.

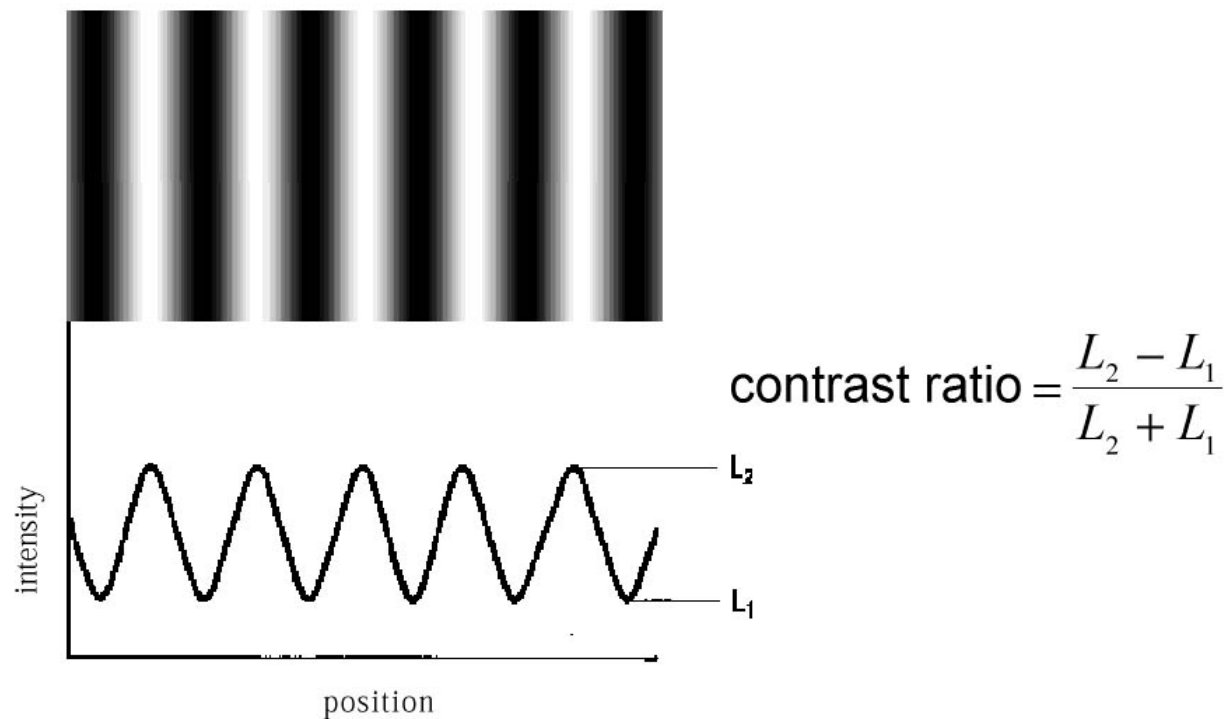
# Inhibition of excitation in the retina

- Receptive field of a ganglion cell (=fiber of the optic nerve) shows „center-surround response“ with both
  - Lateral inhibition
  - Lateral excitation



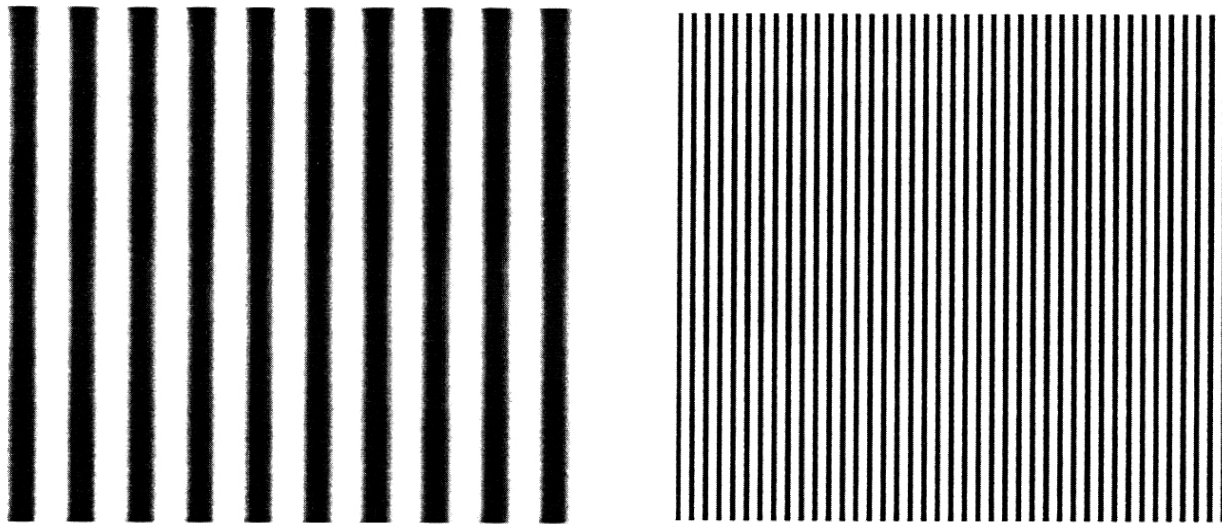
# Sine wave grating

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# MTF of the visual system

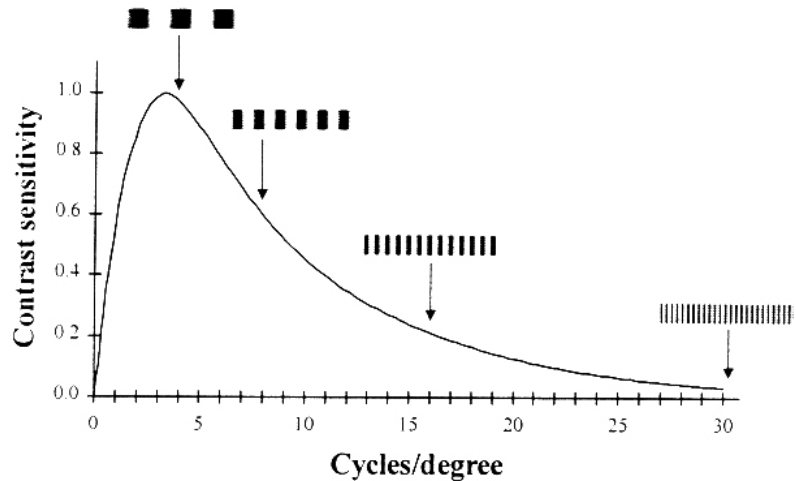
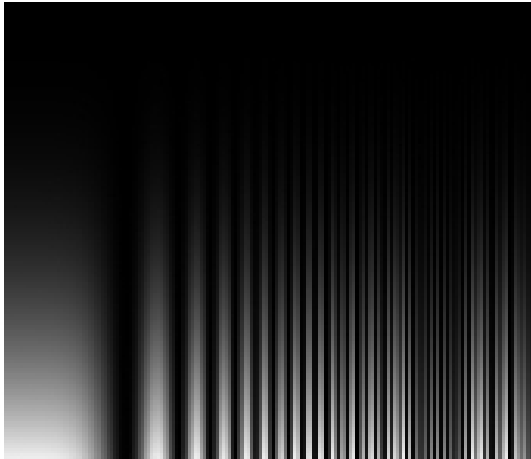
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low- and high-frequency pattern

# MTF: Modulated Sine Wave Grating

MTF – the measure of visual system in frequency domain



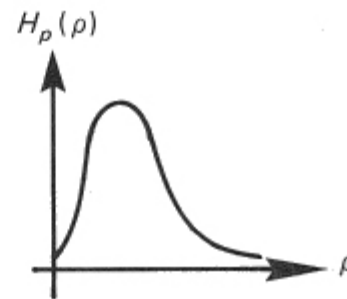
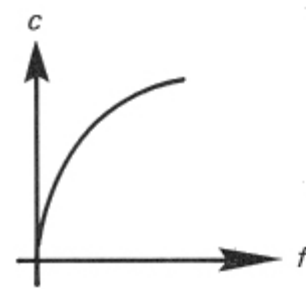
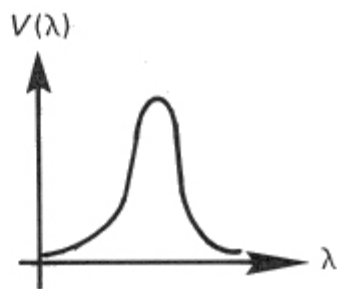
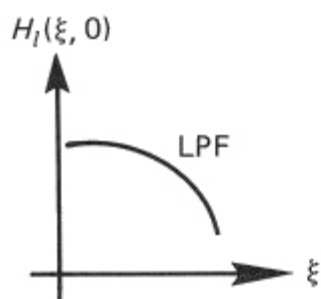
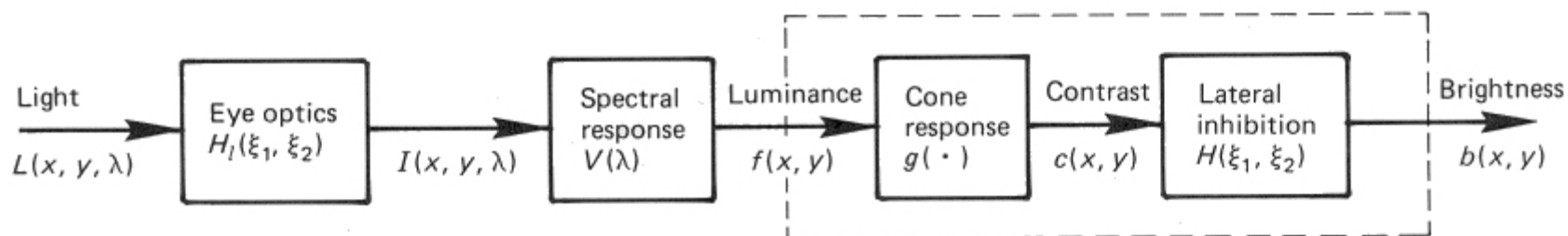
$$H(\xi_1, \xi_2) = H_p(\rho) = A \left[ \alpha + \frac{\rho}{\rho_0} \right] \exp \left[ - \left( \frac{\rho}{\rho_0} \right)^\beta \right]$$

$$\rho = \sqrt{\xi_1^2 + \xi_2^2} \text{ cycles/deg}$$

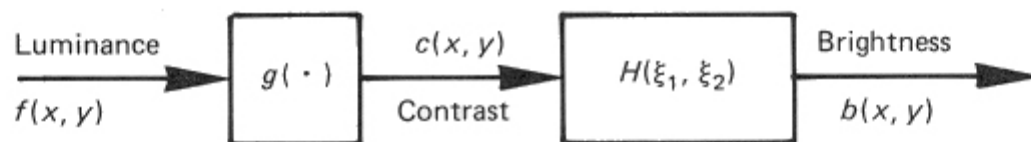
(isotropic approximation)

Lateral inhibition and excitation together lead to a bandpass characteristics of the contrast sensitivity function of the HVS

# Monochrome vision model



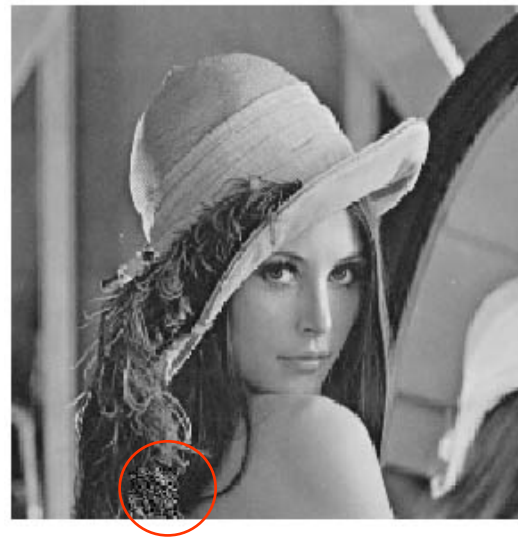
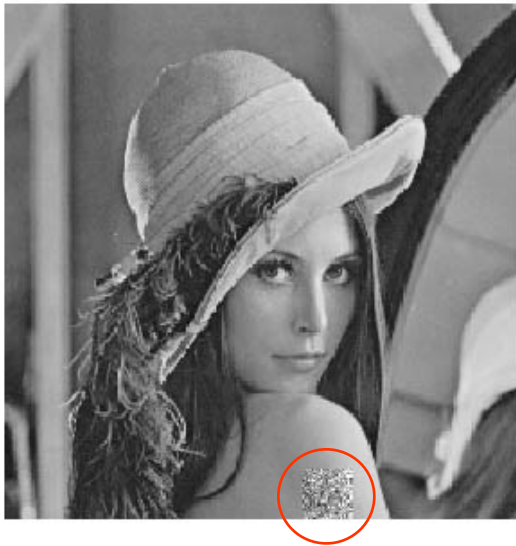
(a) Overall monochrome vision model.



(b) Simplified monochrome vision model.

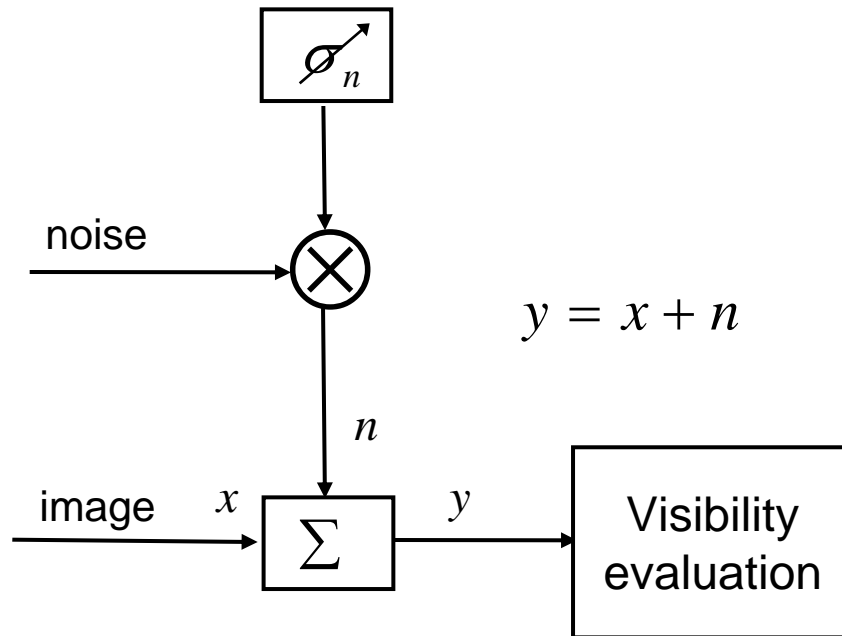
# Visibility function (Higher Order Vision): Masking

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# Noise Visibility Function (NVF)



$$NVF(i, j) \in (0,1)$$

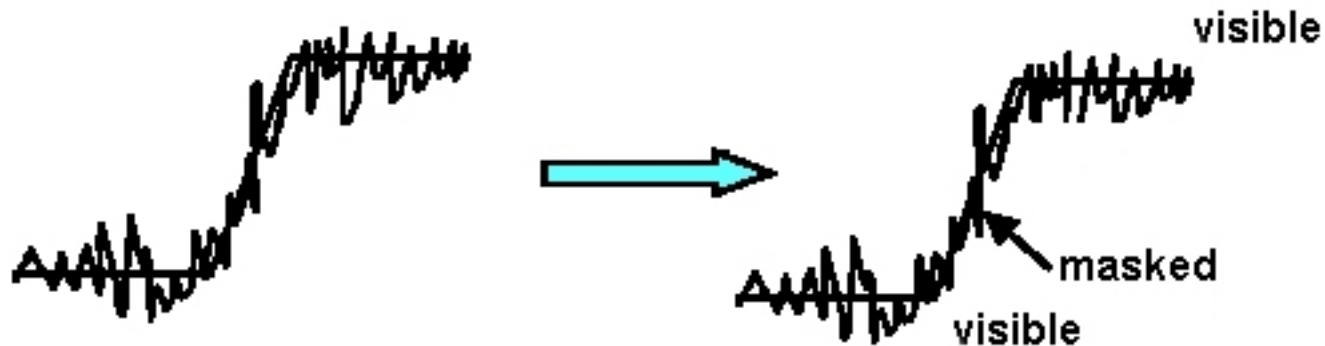
- Behavior of NVF :
- for flat regions -  $NVF \rightarrow 1$ ,
  - for edge & texture regions -  $NVF \rightarrow 0$ .

# Features of the HVS

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## Masking Properties of HVS :

Texture masking



Note: however very sharp edges have higher visibility of distortions.

# Features of the HVS

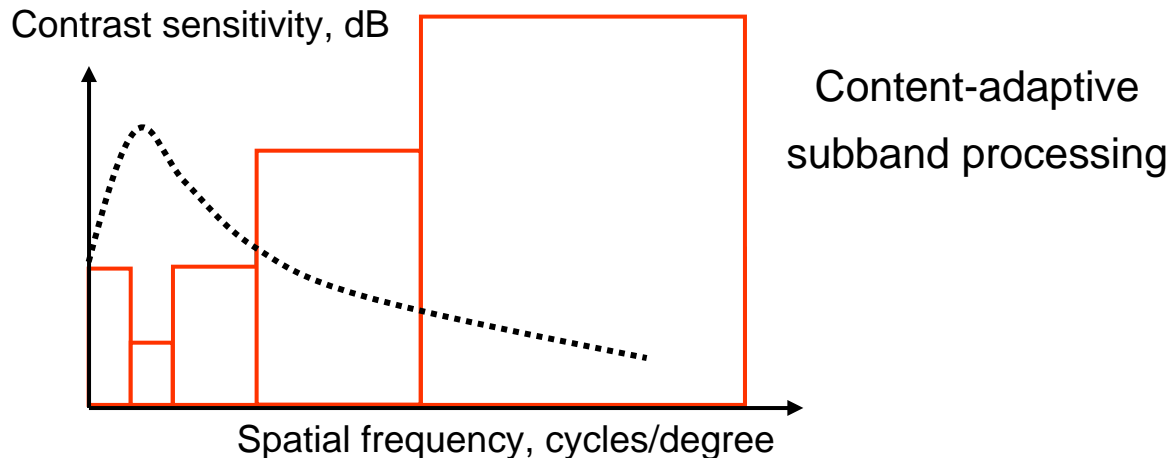
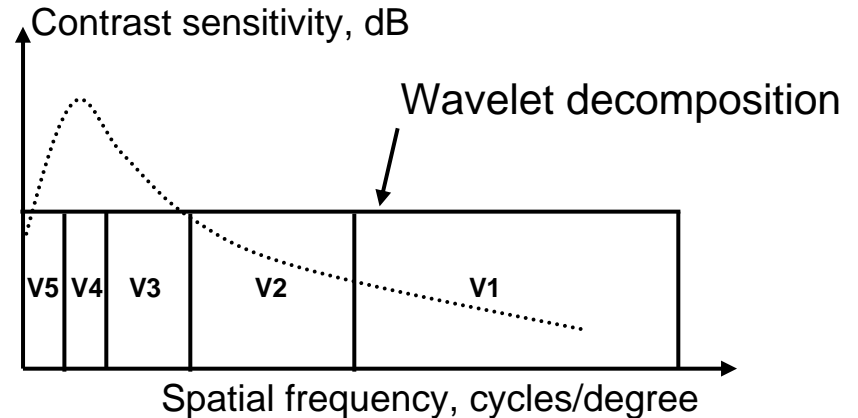
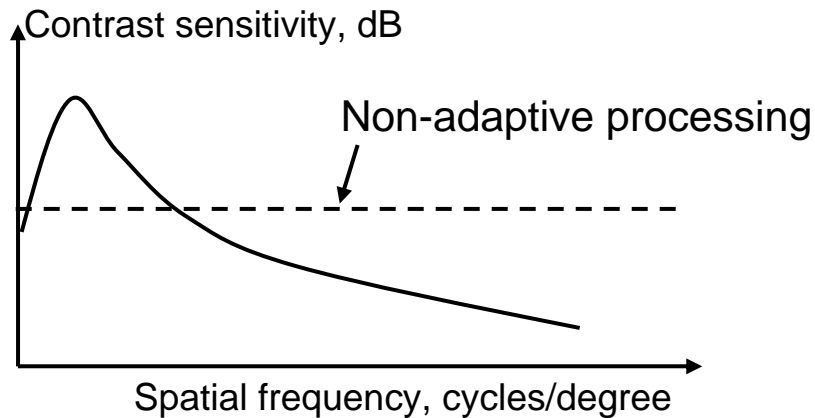
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## Features of the Human Visual System :

- on the global level:
  - Modulation Transfer Function (MTF);
  - anisotropy due to 3 different spatial orientations;
  - multiresolution.
- on the local level:
  - Noise Visibility Function (NVF)

# Features of the HVS

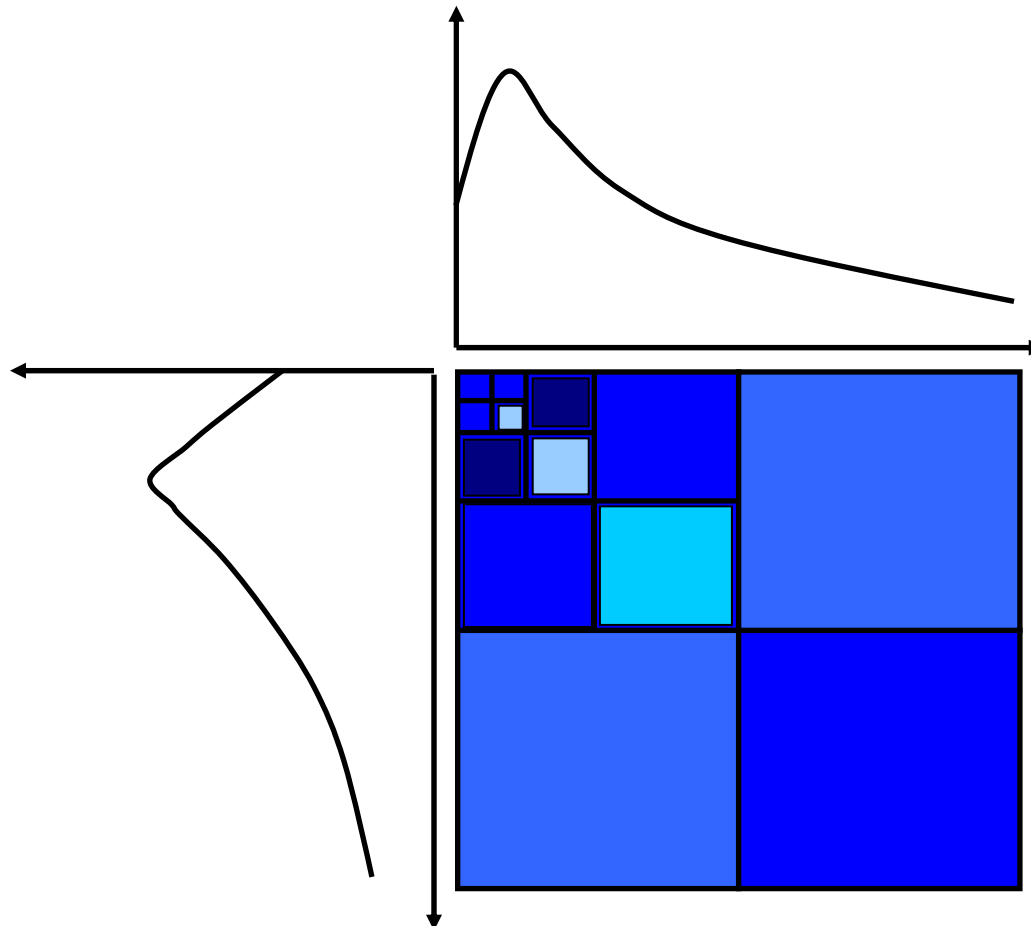
## MTF – global features of the HVS



# Features of the HVS

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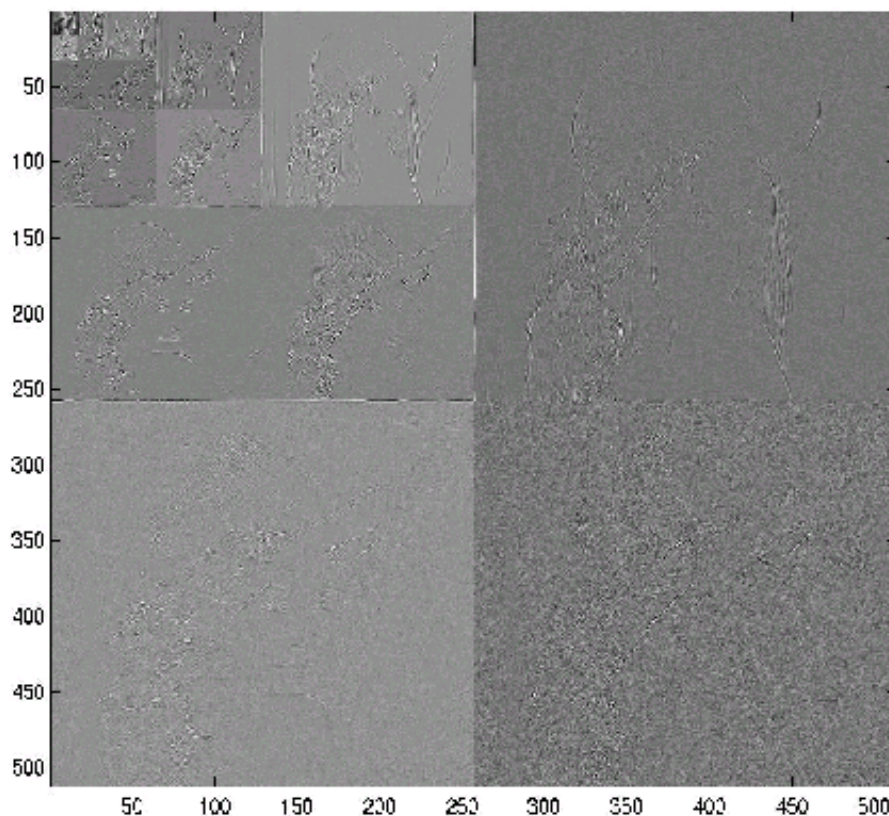
Spatial orientation – global features of the HVS



# Features of the HVS

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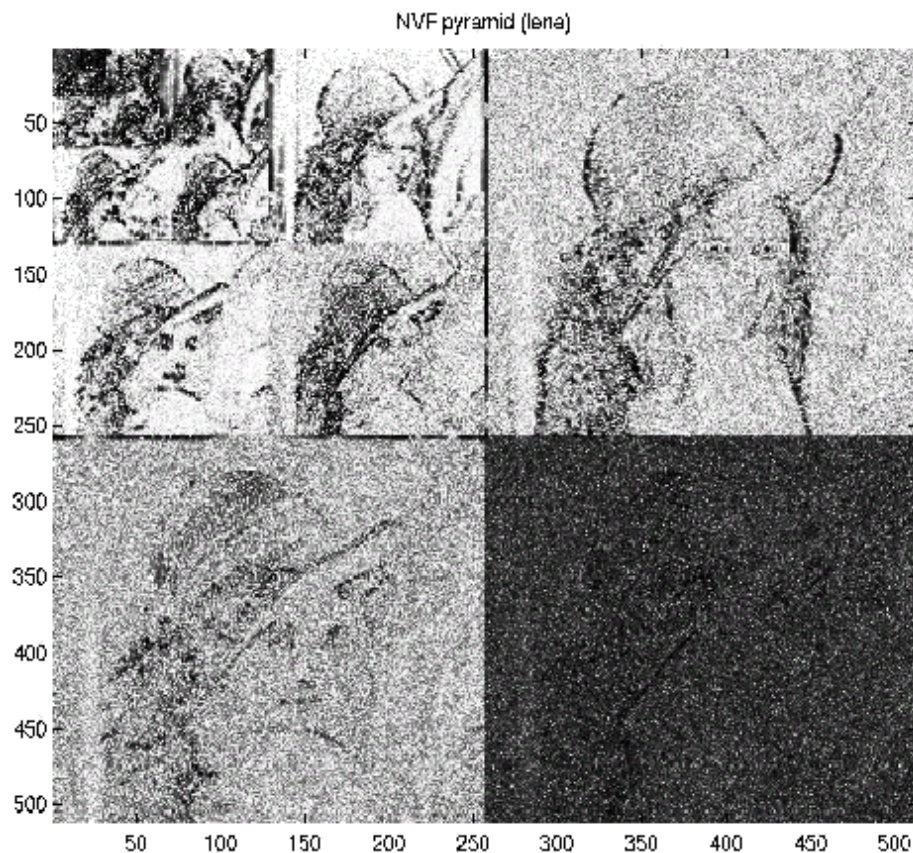
## Multiresolution – global features of the HVS



# Features of the HVS

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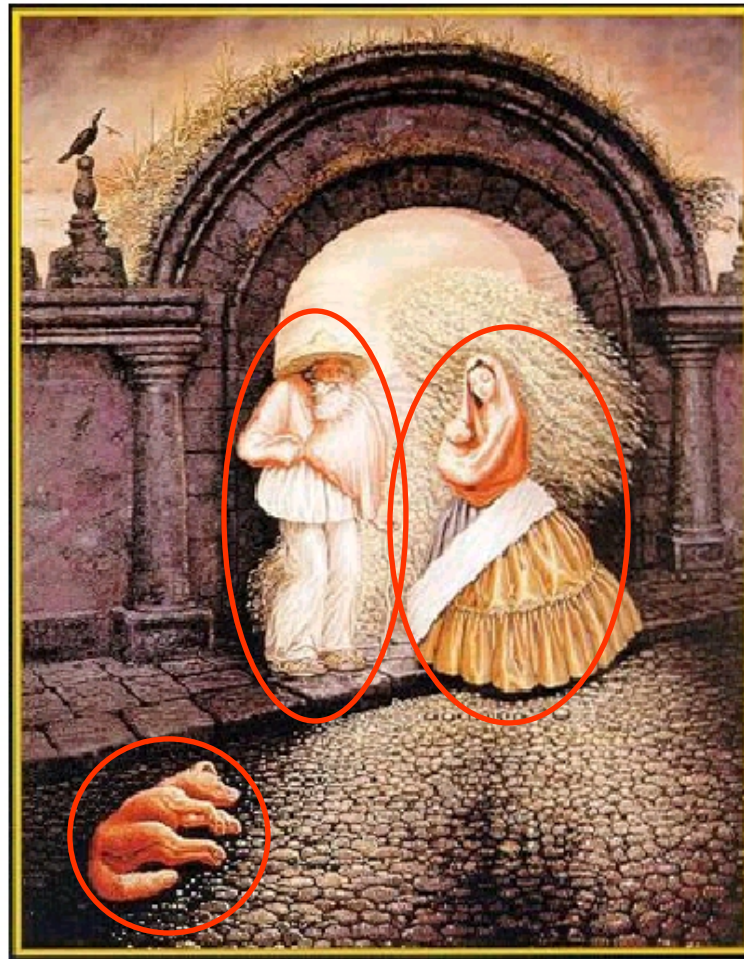
## NVF – local features of the HVS





# Perceptual Ambiguity

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# Perceptual Ambiguity

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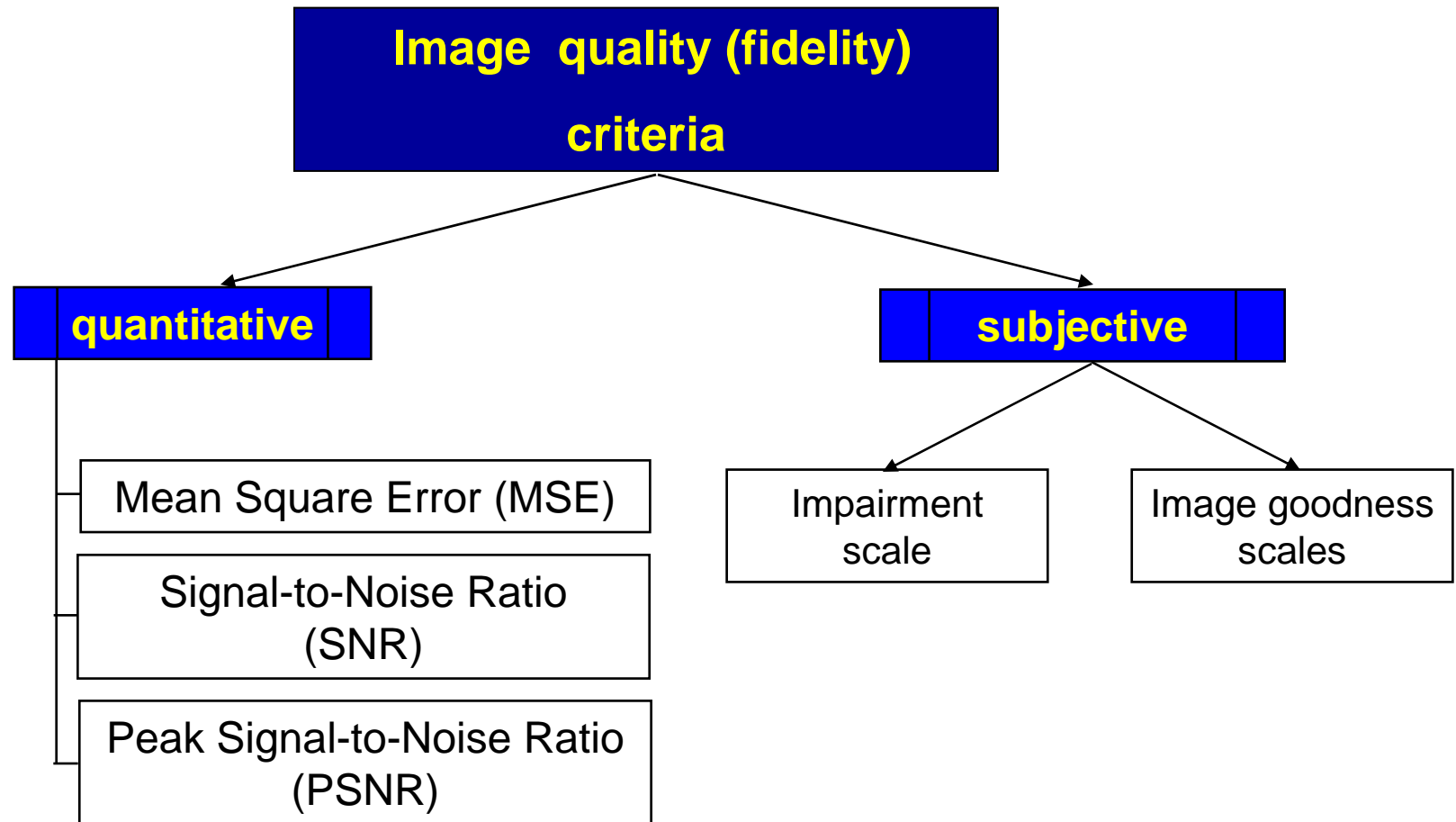
# Perceptual Ambiguity

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# Image quality criteria

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# Image quality criteria

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	<b>Quantitative criteria</b>	
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- MSE (mean square error) criterion:

$$MSE = \frac{1}{MN} \sum_{i=1}^M \sum_{j=1}^N |x(i, j) - x'(i, j)|^2$$

- SNR (signal-to-noise ratio) :

$$SNR, \text{dB} = 10 \log_{10} \frac{\sigma_x^2}{MSE}$$

- PSNR (peak signal-to-noise ratio) :

$$PSNR, \text{dB} = 10 \log_{10} \frac{\max(x)^2}{MSE}$$

# Image quality criteria

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	<b>Subjective criteria</b>	
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- impairment scale :

<b>Q Factor</b>	<b>Quality</b>	<b>Impairment</b>
5	Excellent	Imperceptible
4	Good	Perceptible, but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

# Image quality criteria: Weighted Metrics

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MSE:

$$MSE = \frac{1}{MN} \sum_{i=1}^M \sum_{j=1}^N |x(i, j) - x'(i, j)|^2$$

Weighted MSE:

$$wMSE = \frac{1}{MN} \sum_{i=1}^M \sum_{j=1}^N \left( NVF(i, j) \cdot |x(i, j) - x'(i, j)|^2 \right)$$

PSNR:

$$PSNR, \text{dB} = 10 \log_{10} \frac{\max(x)^2}{MSE}$$

Weighted PSNR:

$$wPSNR, \text{dB} = 10 \log_{10} \frac{\max(x)^2}{wMSE}$$



# Image quality criteria – comparative analysis

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Original image “Barbara”

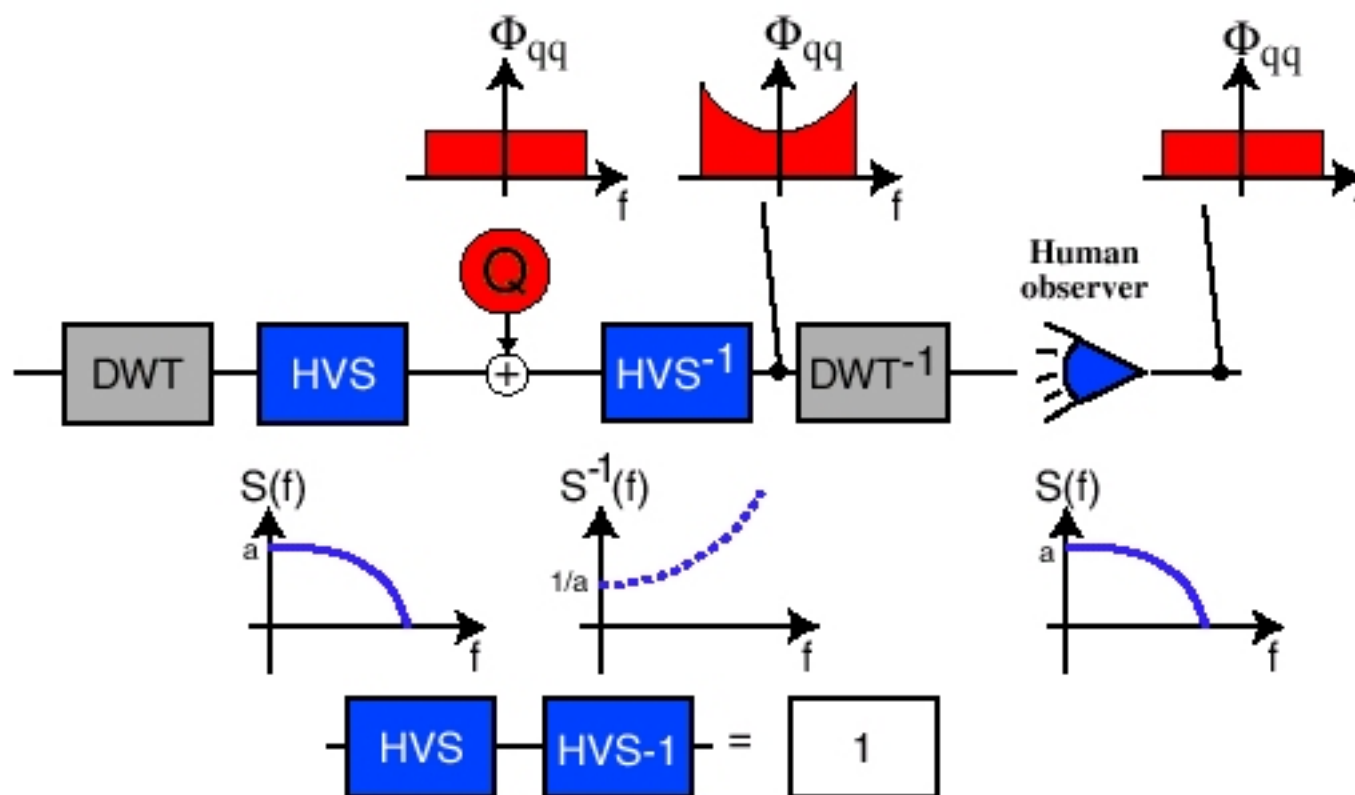


*Added Noise*  
 $PSNR = 24.6$  dB,  
 $wPSNR = 26.4$  dB



Image with perceptually  
adopted noise  
 $PSNR = 24.6$  dB,  
 $wPSNR = 29.3$  dB

# How to exploit the properties of the HVS?





# Features of the HVS – comparative analysis

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Grayscale image



PSNR=33 dB



PSNR=37 dB



Original image

# Features of the HVS – comparative analysis

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Color image



PSNR=37 dB



Original image



PSNR=35 dB

# HVS: conclusions

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- Spatial frequency components visible up to 60 cpd.
- Logarithmic relationship between luminance and subjective perceived brightness.
- Lateral inhibition -> spatial bandpass character.
- Resolution of HVS depends on the wavelength.
- Resolution of HVS depends on the orientation.
- Visibility threshold is high for the flat regions and in the vicinity of very sharp edges.
- Visibility of distortions is decreased in the texture regions due to perceptual masking.