

# Human-vision Friendly Processing for Images and Graphics

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# Outline of Tutorial

- Introduction
- Relevant physiological & psychological phenomena
- Basic Computational Modules
- Perceptual Visual Processing & Applications
- Concluding Remarks, Further Discussion & Possible Future Work
- List of Most Relevant References (for further reading)



A picture is worth 1000 words



# Current Problem in Visual Processing System Design

The Human Visual System (HVS):

the ultimate receiver of most processed  
images, video, and graphics



Gap in most systems:

target: human consumption/appreciation  
technical design: non-perceptual criteria

Perceptual modeling:

user-oriented  
performance booster

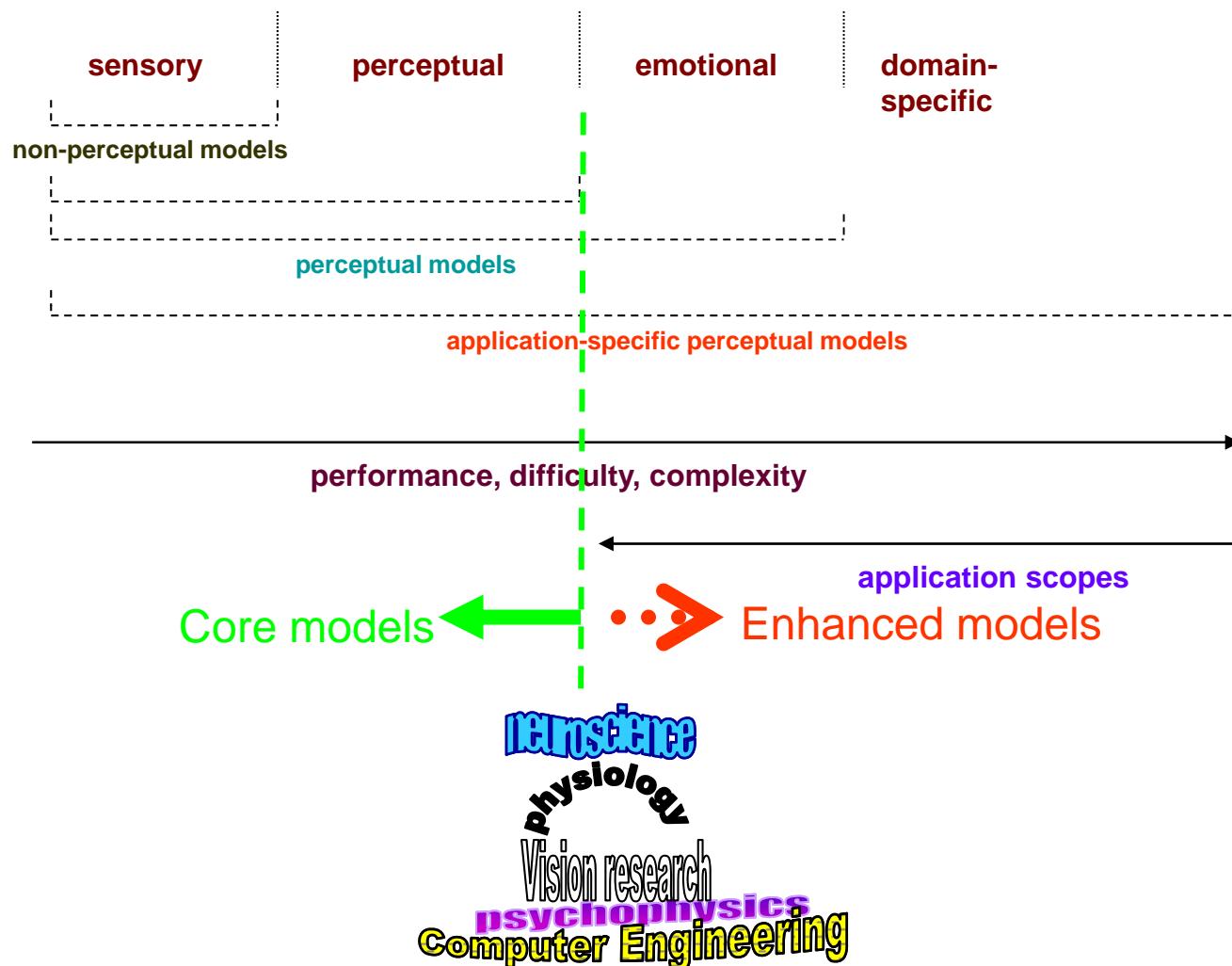
# Traditional Signal Quality Definitions & Measures

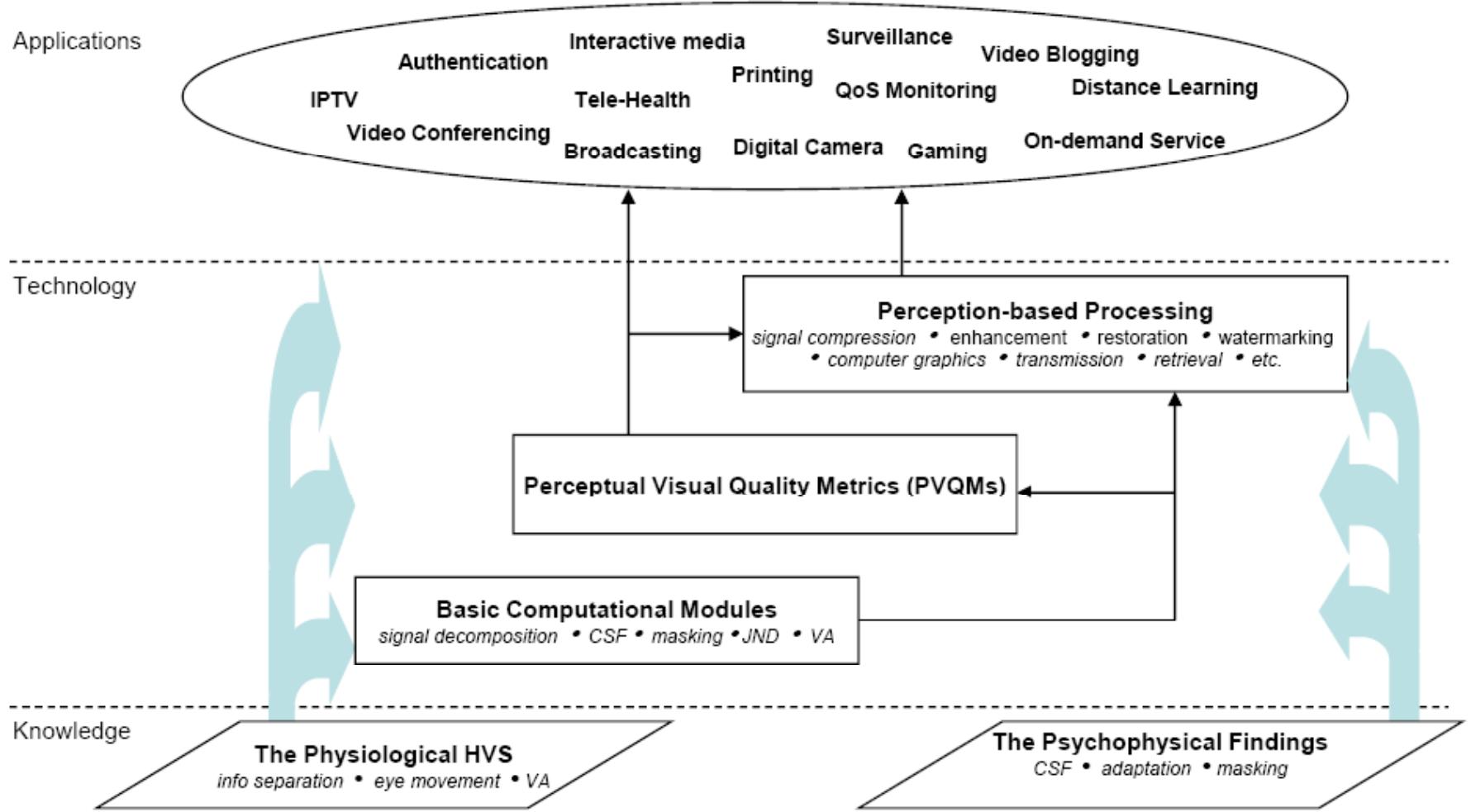
- MSE (Mean Square Error)
- SNR (Signal Noise Ratio)
- PSNR (Peak SNR)
- QoS (Quality of Service)
- or their relatives

# Possibilities of Perceptual Evaluation

- **Subjective viewing tests**
  - ITU BT 500 standard, etc.
  - MOS (mean opinion score)
  - Shortcomings
    - Expensive, time consuming
    - Not suitable for automatic *in-loop* processing  
e.g., encoding, transmission, relaying, etc.
    - Not always reliable  
depending on viewers' physical conditions, emotional states, personal experience, display context
- **Objective visual quality metrics (VQMs)**
  - MOS prediction
  - HVS modeling
    - physiology
    - psychophysics
  - Difficulties
    - inadequate understanding of the HVS
    - difficulty in modeling
    - computational complexity

# Perceptual Modeling

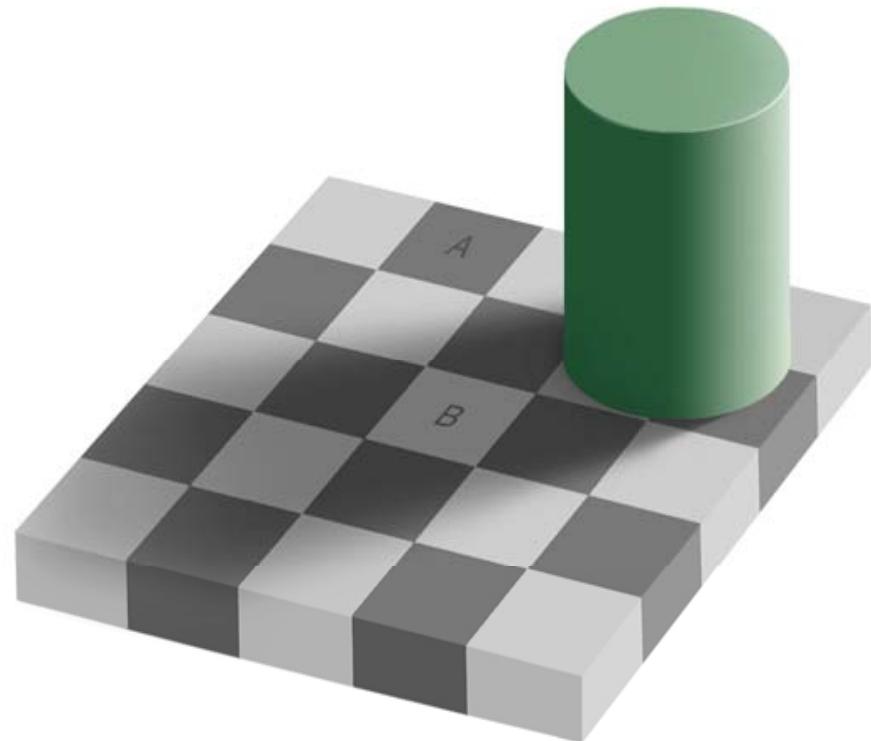


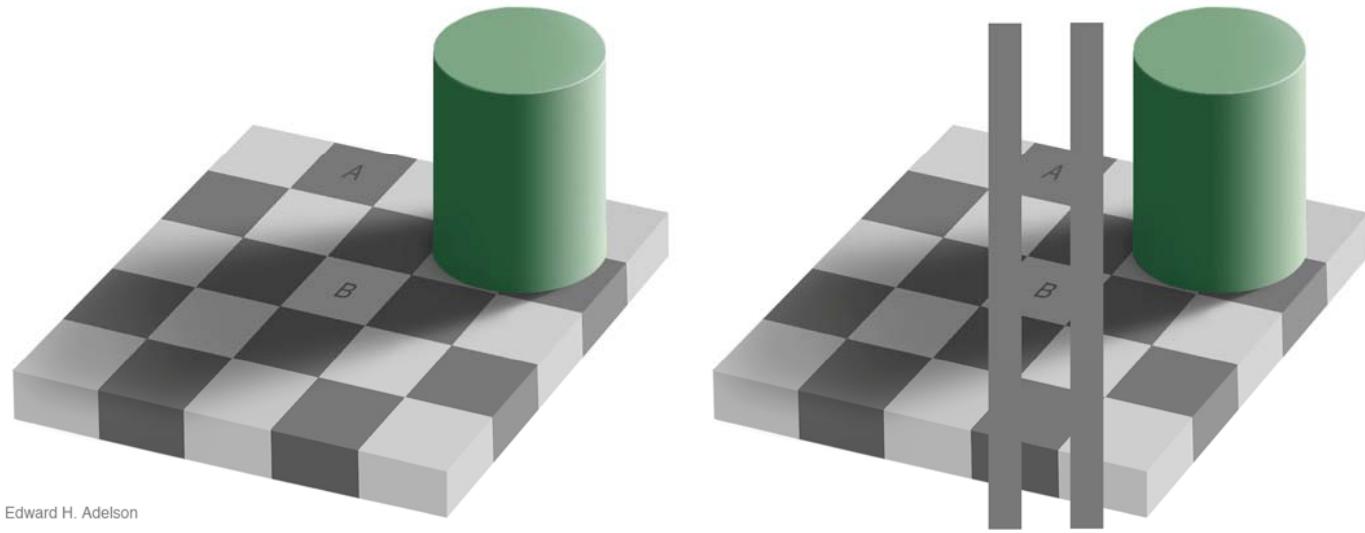


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# Which square is brighter, A or B?



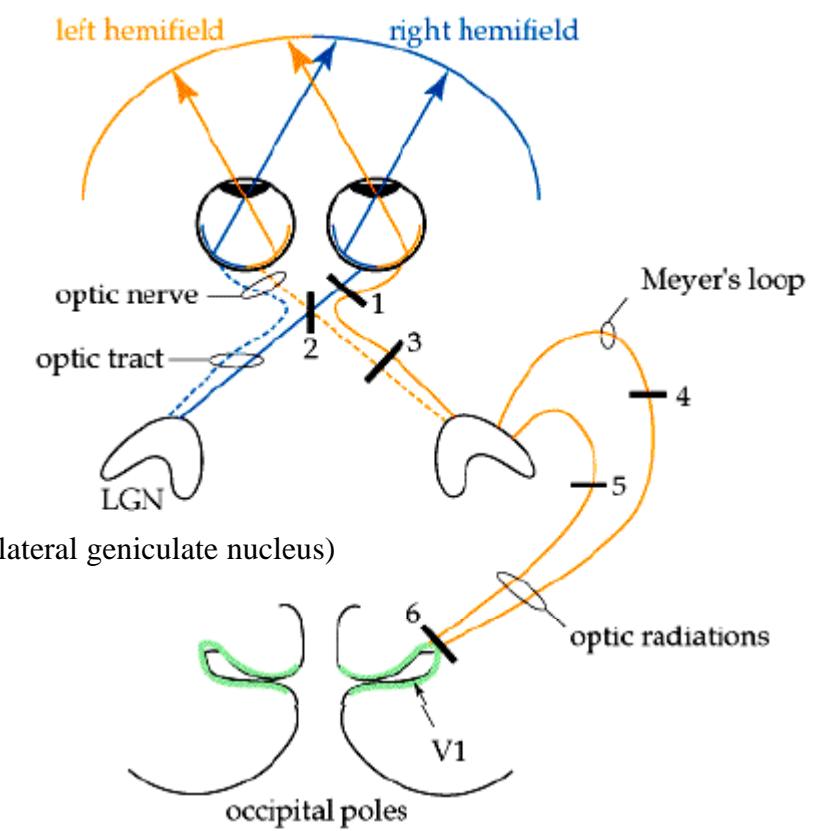
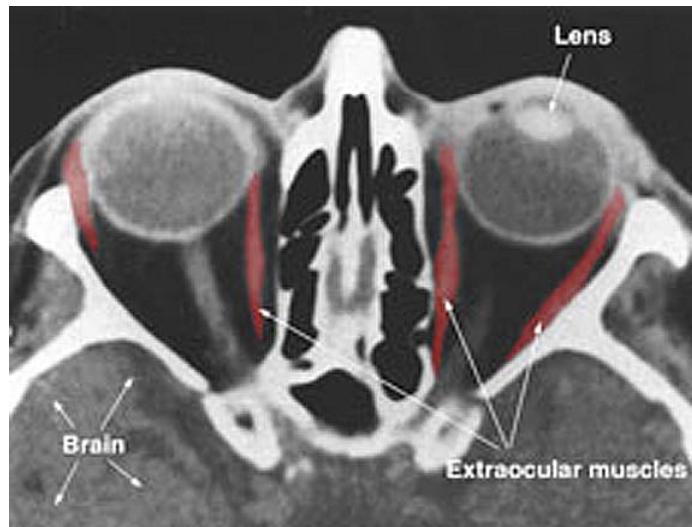


Edward H. Adelson

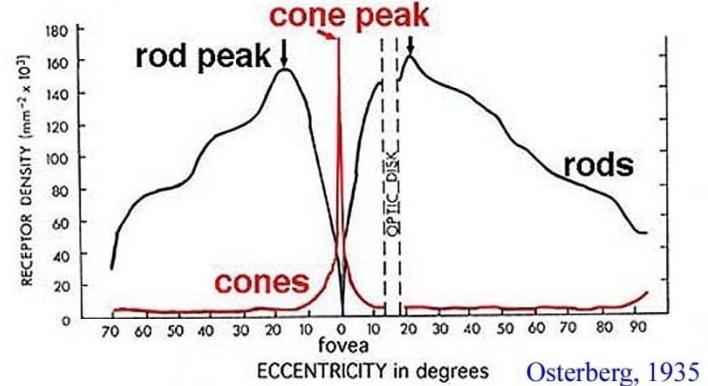
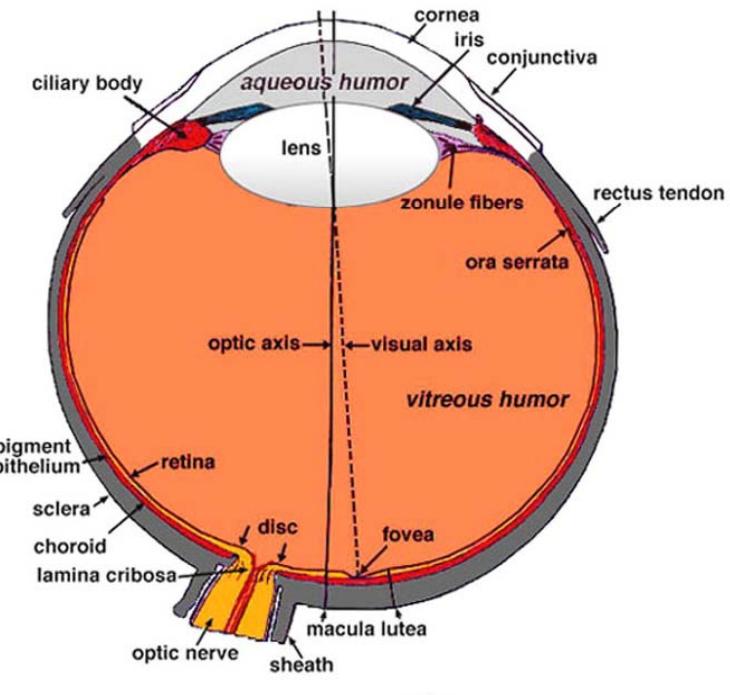
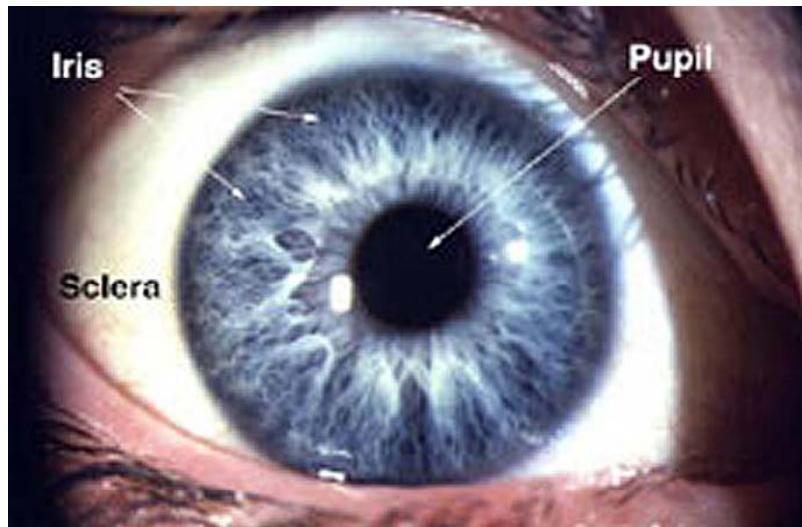
## Adelson's “Checker-shadow illusion”

[http://web.mit.edu/persci/people/adelson/checkershadow\\_illusion.html](http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html)

# Visual Pathways



# Human Eyes



Osterberg, 1935

# The HVS: Specialized Processes & Information Differentiation

- Cones
  - fovea on the retina
  - color vision
    - S-cones: blue
    - M-cones: green
    - L-cones: red
  - high visual acuity

## The HVS: Specialized Processes & Information Differentiation (cont'd)

- two pathways from the retina to the primary visual cortex (V1)
  - **Magnocellular pathway**
    - majority of the nerve fibres
    - thin fibres
    - slow in info transfer
    - all color and contrast info
  - **Pavocellular pathway**
    - thick fibres
    - fast in information transfer
    - all transient, motion related info
    - not responsive to chromatic info

## The HVS: Specialized Processes & Information Differentiation (cont'd)

- The visual cortex (V1~V4) distinguish
  - orientation
  - form
  - color
  - motion

# Eye Movement

- spontaneous smooth-pursuit eye movement (SPEM)
  - tend to track moving objects
  - reduce the retinal velocity of image
- other eye movement
  - natural drift movement
    - responsible for perception of static images
    - very slow (0.8–1.5 deg/s)
  - saccadic movement
    - responsible for rapidly moving objects

# Visual Attention

- Selectivity
  - selective awareness of the sensory environment
  - selective responsiveness to visual stimuli
- Two types
  - bottom-up: external stimuli
  - top-down: task related
- Three stages for bottom-up process
  - pre-attentive
    - No capacity limitation
    - all the information can be processed (color, orientation, motion, curvature, size, depth, luster, shape)
  - Attention
    - feature integration
    - competition
  - Post-attention
    - improved search efficiency

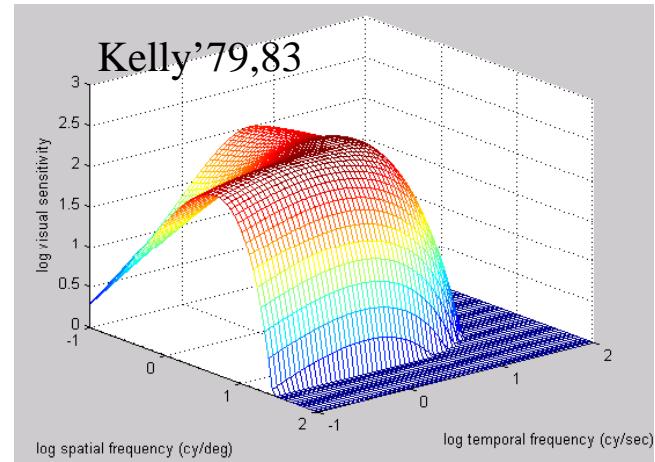
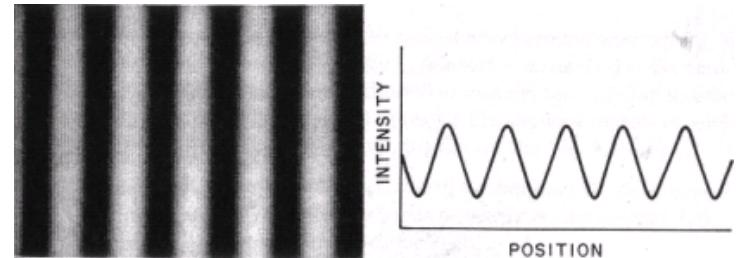
# Psychophysical Experiments

Weber-Fechner law

Contrast Sensitivity Function (CSF)

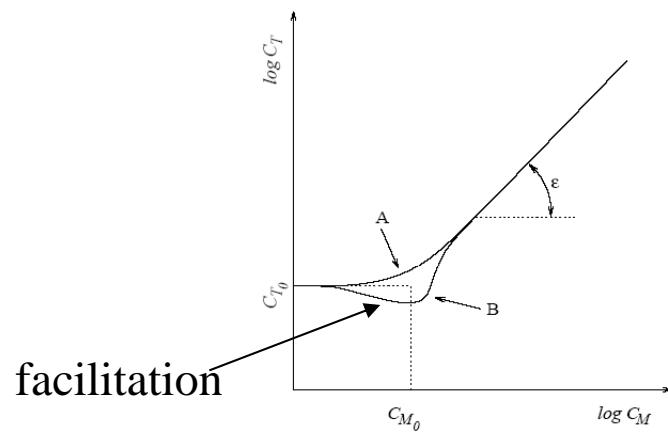
sine-wave gratings

DCT basis functions



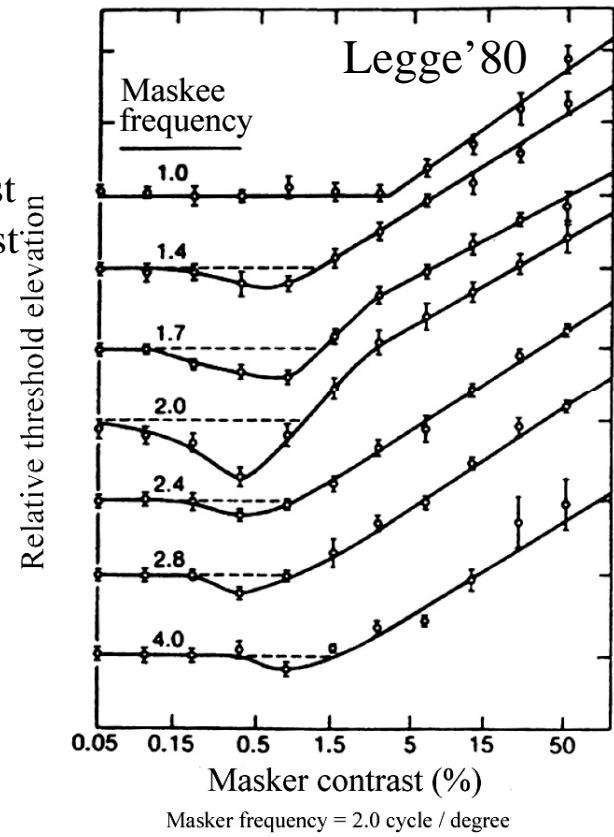
# Contrast masking:

relationship between maskee and masker dependency on orientations



$C_T$ : maskee contrast  
 $C_M$ : masker contrast

The change of contrast masking with maskee's frequency

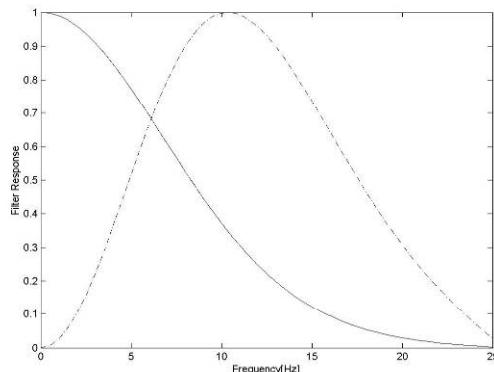


# Outline of Tutorial

- Introduction
- Relevant physiological & psychological phenomena
- Basic Computational Modules
  - Signal Decomposition
  - Just-noticeable Difference (JND)
  - Modeling Visual Attention (VA)
- Perceptual Visual Processing & Applications
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# Temporal Decomposition

- Physiological evidence
  - two main visual pathways
  - visual cortex
- Signal decomposition
  - Implemented as FIR/IIR filters
    - sustained (low-pass) channel
    - transient (band-pass) channel

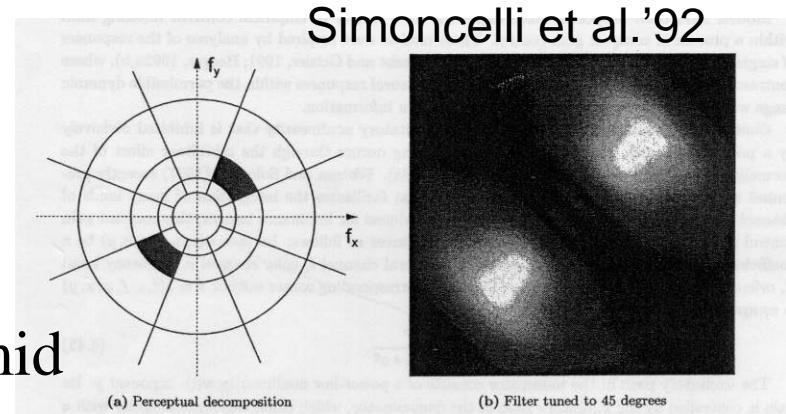


tap	0	1	2	3	4	5	6	7	8
$h_{su}(t)$	0.0004	0.0121	0.0672	0.2364	0.3677	0.2364	0.0672	0.0121	0.0004
$h_{tr}(t)$	-0.0260	-0.0567	-0.2242	0.0337	0.5289	0.0337	-0.2242	-0.0567	-0.0260

Coefficients for the sustained and transient 9-tap FIR filters

# Spatial Decomposition

- Filters
  - Gabor, Cortex, wavelets
  - Gaussian/sterrable pyramid
- Stimuli: orientations, frequencies



# Just-noticeable Difference (JND)

- JND: the visibility threshold below which any change cannot be detected by the HVS
  - e.g., 75% of the subjects
- difference: not necessarily distortion
  - better not to say “just-noticeable distortion”
    - Edge enhancement
    - Removal of flickers
    - Post-processing
- explicit model is helpful
- 2 JNDs, 3 JNDs, ... can be also determined

# JND in DCT Subbands

General formula in DCT subbands:

$$s(n, i, j) = t_{s-csf}(n, i, j) \prod_p \alpha_p(n, i, j)$$

*n*: DCT block index  
*i,j*: DCT subband

where  $t_{s-csf}(n, i, j)$  : base threshold due to spatial CSF

$\alpha_p(n, i, j)$  : elevation parameter due to luminance adaptation, intra-band masking, and inter-band masking, etc.

# Modeling Spatial CSF

parabola equation (Ahumada & Peterson'92):

$$\log T = \log T_{min} + K(\log f - \log f_p)^2$$

$T$ : visibility threshold due to spatial CSF

$f$ : spatial frequency

vertex location:  $f_p = 6.78 \left( \frac{L}{300} \right)^{\beta_f}$

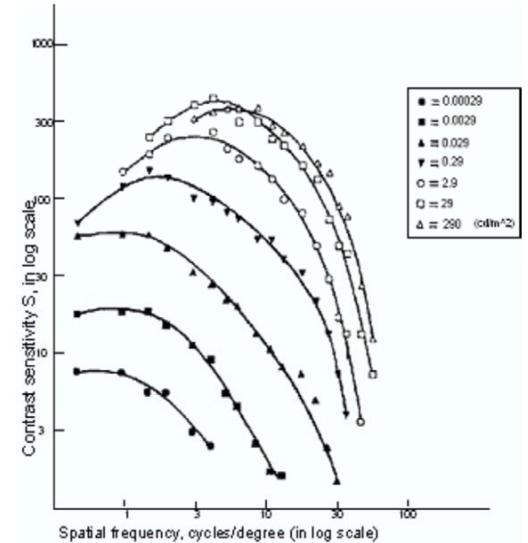
threshold at  $f_p$ :  $T_{min} = \begin{cases} 0.142 \left( \frac{L}{13.45} \right)^{0.649} & \text{if } L \leq 13.45 \text{ cd/m}^2 \\ \frac{L}{94.7} & \text{otherwise} \end{cases}$

(Van Nes & Bouman'67)

$L$ : the luminance

other parameters:  $\beta_K = \begin{cases} 0.0706, & \text{if } L \leq 300 \text{ cd/m}^2 \\ 0, & \text{otherwise} \end{cases}$        $\beta_f = \begin{cases} 0.182, & \text{if } L \leq 300 \text{ cd/m}^2 \\ 0, & \text{otherwise} \end{cases}$

$$K = 3.125 \left( \frac{L}{300} \right)^{\beta_K}$$



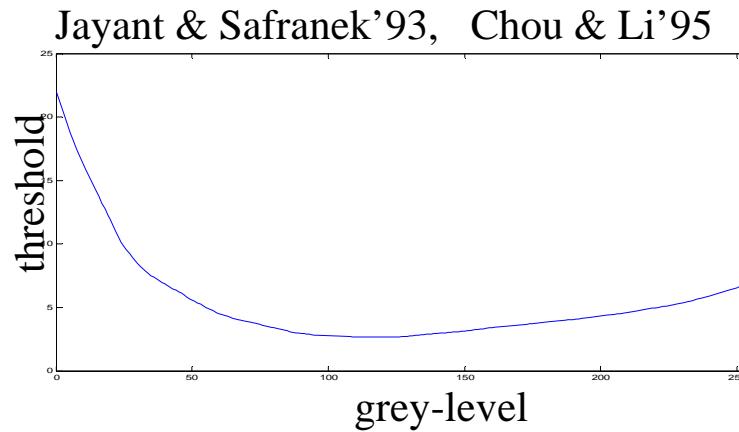
# Luminance Adaptation

- a simplified model with Weber-Fechner law  
(Watson'93)

$$\alpha_{\text{lum}}(n) \sim c^{0.649}(n,0,0)$$

where  $c(n, 0, 0)$ : DC coefficient of the block

- more realistic modeling



# Contrast Masking

- Intra-band Masking

(Watson'93, Hontsch & Karam'02)

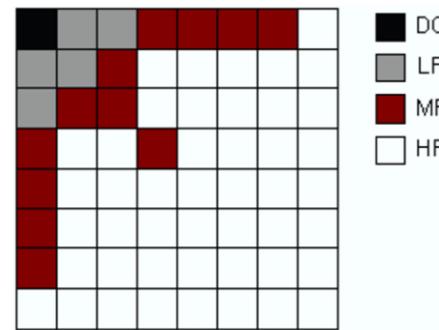
$$\alpha_{intra}(n, i, j) = \max(1, |\frac{c(n, i, j)}{t_{s-csf}(i, j) \cdot \alpha_{lum}(n)}|^{\zeta})$$

where  $0 < \zeta < 1$

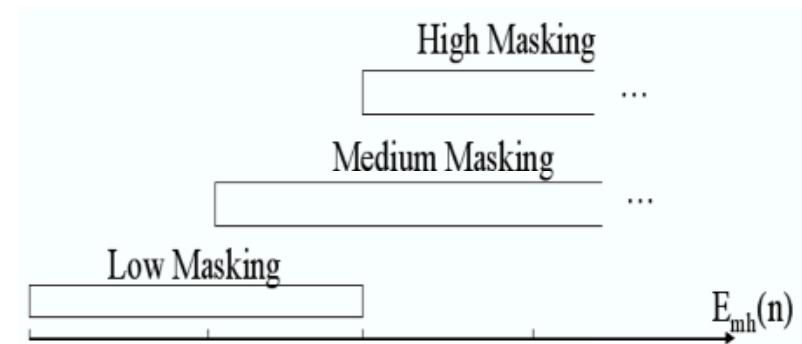
# Contrast Masking (cont'd)

- Inter-band Masking

(Tong&Venetsanopoulos'98)



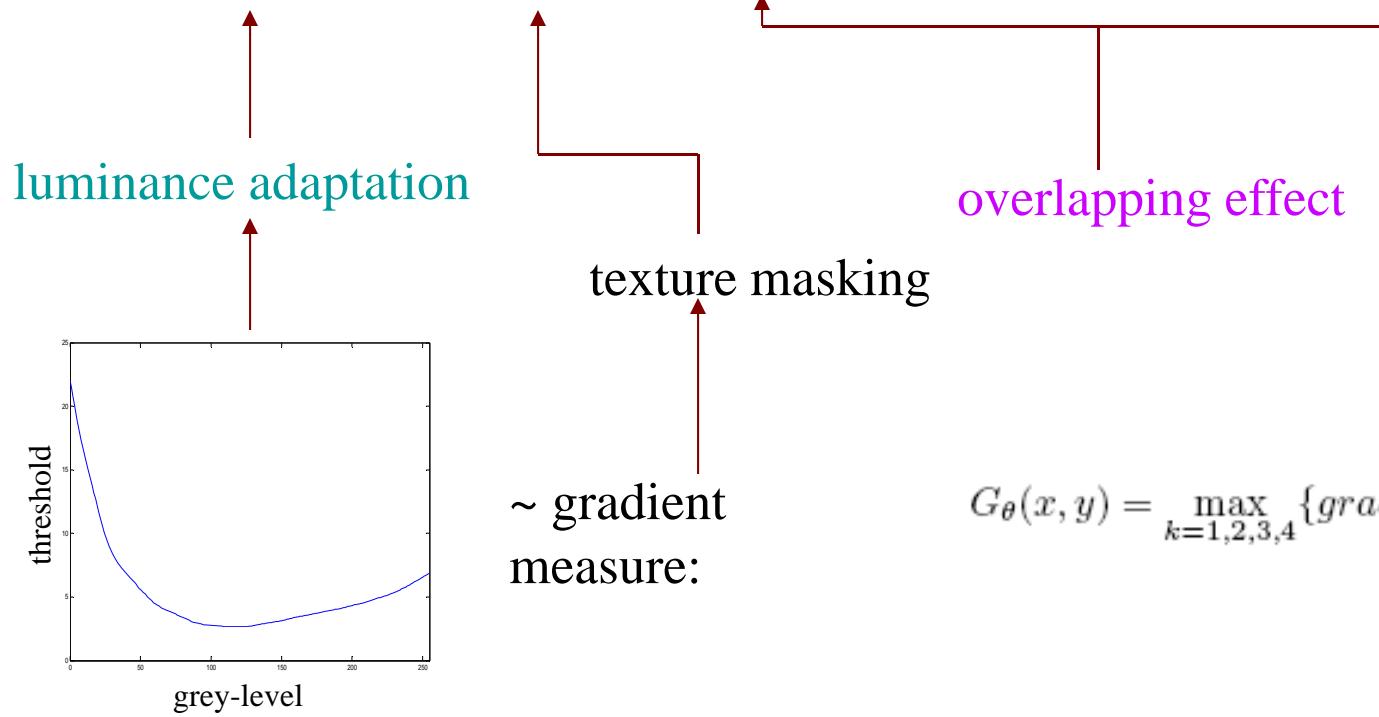
$E_{mh}(n)$ : energy in MF and HF



# JND with Pixels

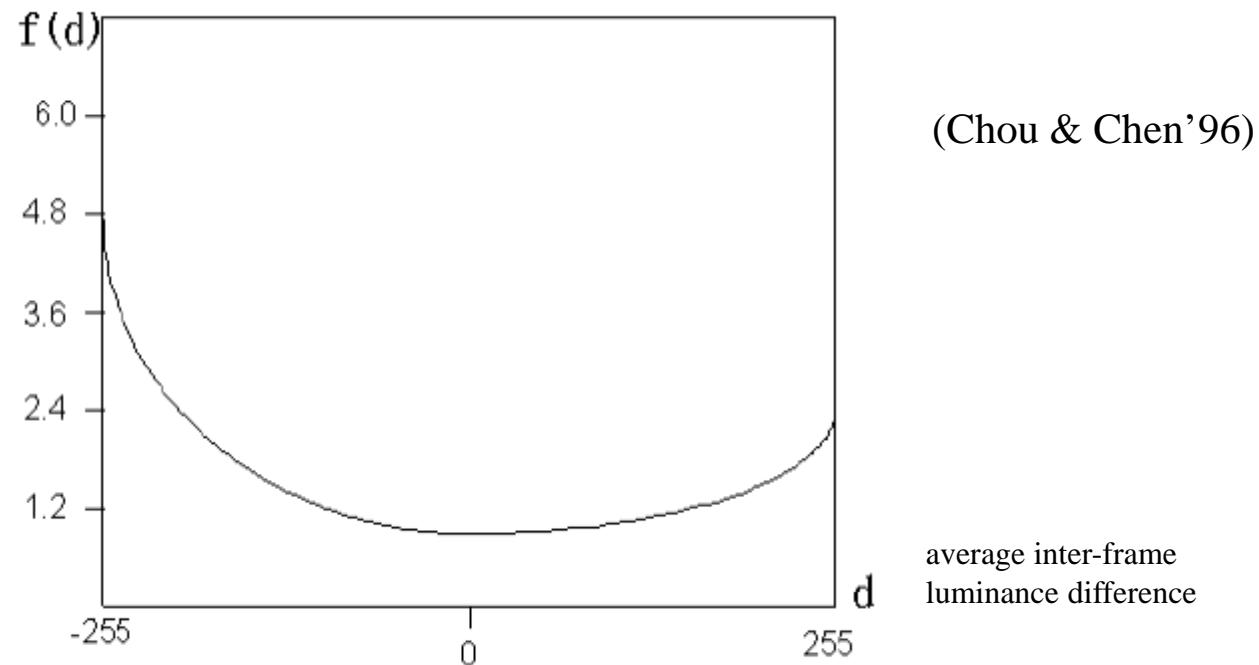
Yang, et al.'05

$$P(X, Y) = T^l(X, Y) + T^t(X, Y) - C^{lt}(X, Y) \cdot \min\{T^l(X, Y), T^t(X, Y)\}$$



$$G_\theta(x, y) = \max_{k=1,2,3,4} \{grad_{\theta,k}(x, y)\}$$

# Temporal Masking Effect



increase of masking effect with increase in interframe changes

# Eye movement model

(Daly'01)

retinal image velocity:  $v(n,t) = v_I(n,t) - v_E(n,t)$

image plane object velocity in retina  
if no eye motion were involved

eye movement velocity

# *Modeling Visual Attention (VA)*

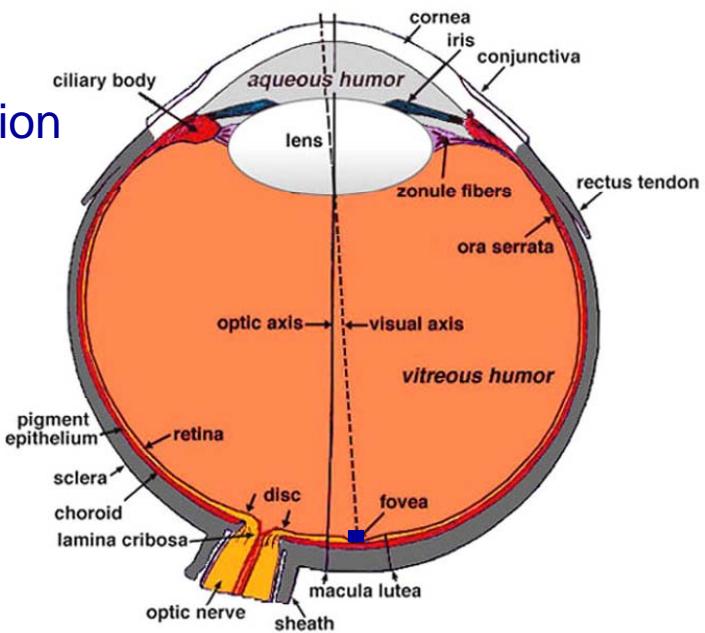
The VA --

- a result of the million years' evolution
- fovea in retina
- eye movement

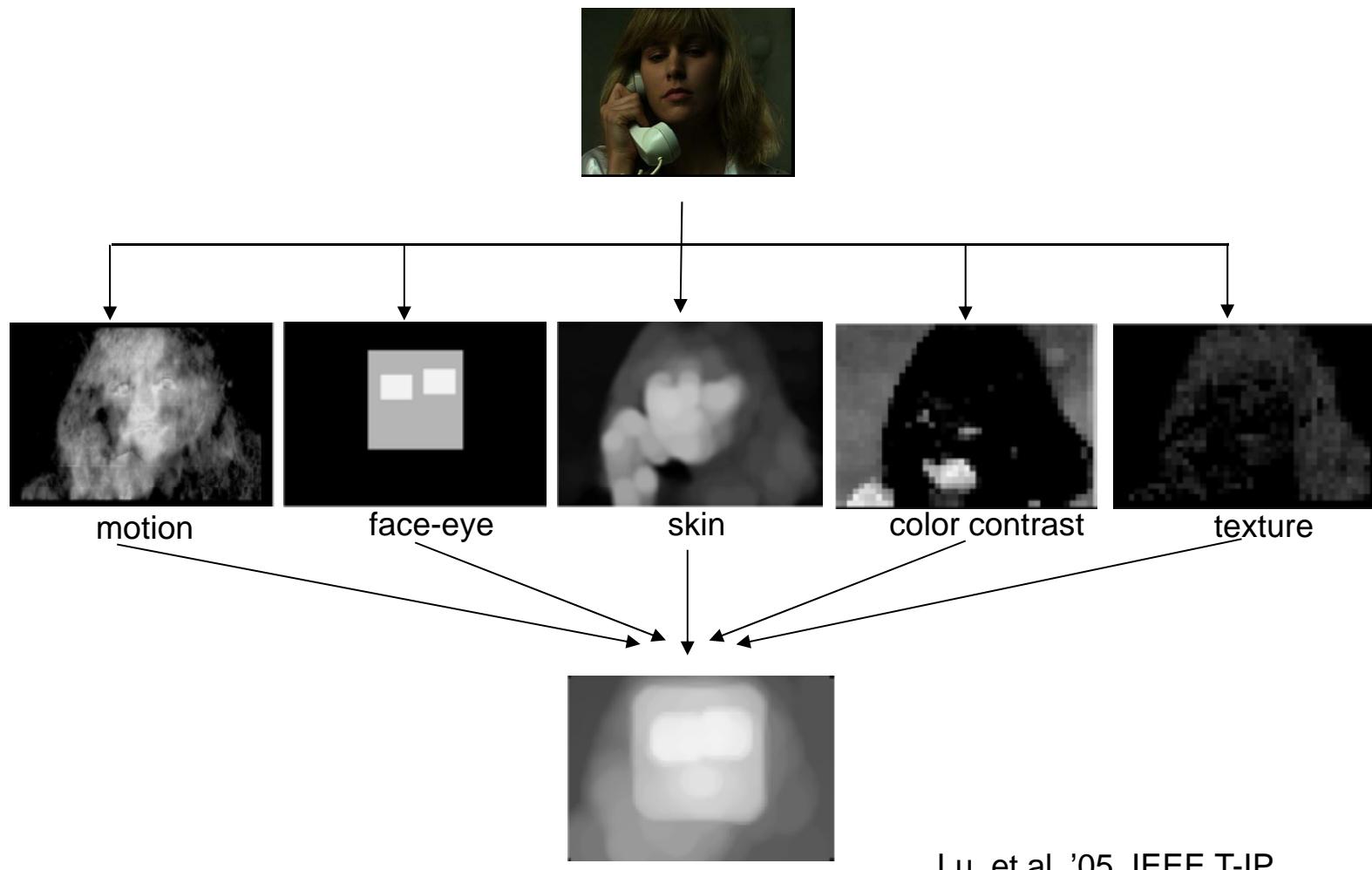
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Therefore, the HVS--

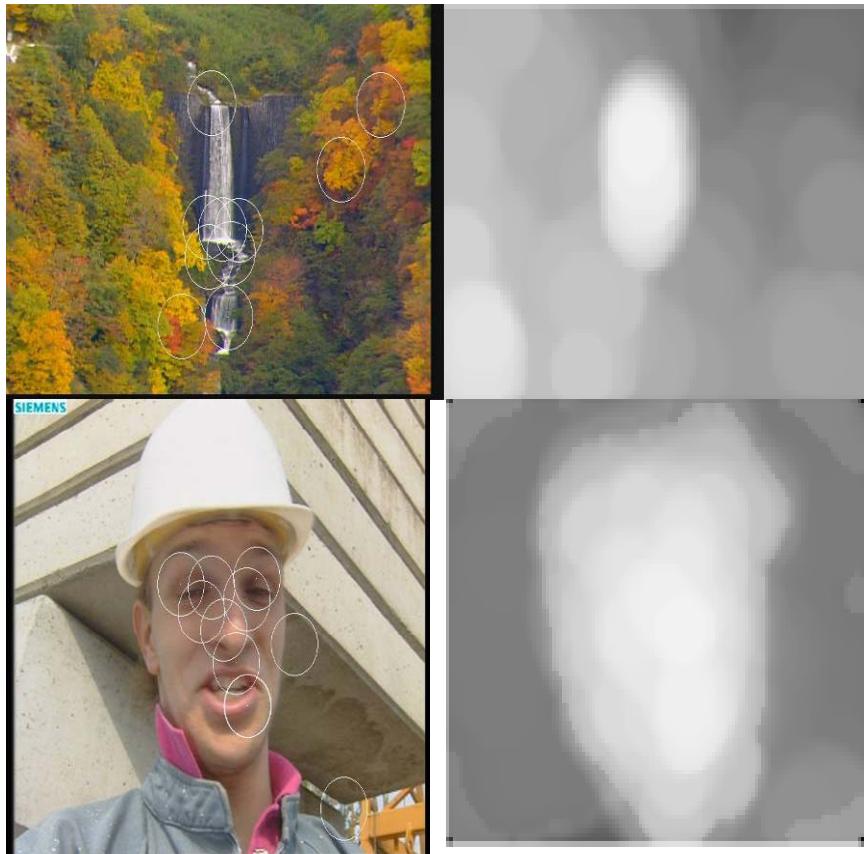
- selective sensor
- with limited source
  - “processing power”
  - “internal memory”



## Auto-generation of visual attention map

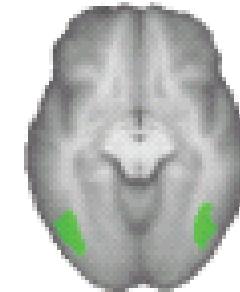


## In line with eye tracking



## Correspondence with fMRI

Background Scene Processing   Object Processing



Lee, et al.'07

Overall visual sensitivity  
--modulation of JND by VA  
--both local & global features

## various eye trackers

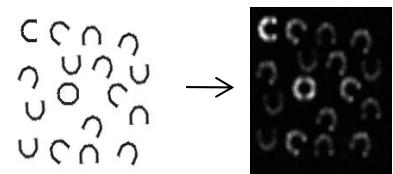


# Alternative approach to detect bottom-up VA

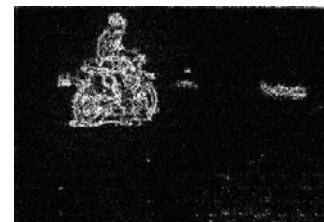
For an image  $I(x; y)$ ,

*Fourier Transform*     $A(u, v) e^{j\phi(u, v)}$

VA:       $R(x, y) = IFT(e^{j\phi(u, v)})$



(Hou & Zhang'07)



# Influence from audio/speech

- Integration of “aural attention”
- Multimedia: correlation & interaction of difference media
- More often than not, presented simultaneously
- Examples in joint modelling
  - Ma, et. al. '05
  - You, et. al. '07

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# Visual Quality Gauge

Why a traditional metric fails



$$MAE = \frac{1}{XY} \sum_{x=1}^X \sum_{y=1}^Y |\Delta d(x, y)|$$

$$MSE = \frac{1}{XY} \sum_{x=1}^X \sum_{y=1}^Y MAE^2$$

$$PSNR = 10 \lg \frac{A^2}{MSE}$$

major reasons for failure:

not every  $\Delta d(x, y)$  

- is noticeable
- results in distortion
- receives same attention

 local characteristics  
 global characteristics

# Noticeable Contrast Changes

$$c(x, y) = \begin{cases} 0 & \text{if } |I(x, y) - \overline{I(x, y)}| \leq jnd(x, y) \\ \frac{|I(x, y) - \overline{I(x, y)}|}{jnd(x, y)} & \text{otherwise} \end{cases}$$

$\overline{I(x, y)}$  is calculated in a image neighborhood

# *New Visual Quality Metric*

- Discrimination of  $c(x,y)$

$c^+_{ne}$ :  $c$  increase at non-edge pixels—*degradation*

$c^-_{ne}$ :  $c$  decrease at non-edge pixels—*degradation*

$c^+_e$ :  $c$  increase at edge—*enhancement*

$c^-_e$ :  $c$  decrease at edge contrast—*the worst degradation*

$$D = \alpha_1 c^-_{ne} + \alpha_2 c^+_{ne} + \alpha_3 c^-_e - \alpha_4 c^+_e$$

where  $\alpha_3 > \max(\alpha_1, \alpha_2) > \alpha_4 > 0$

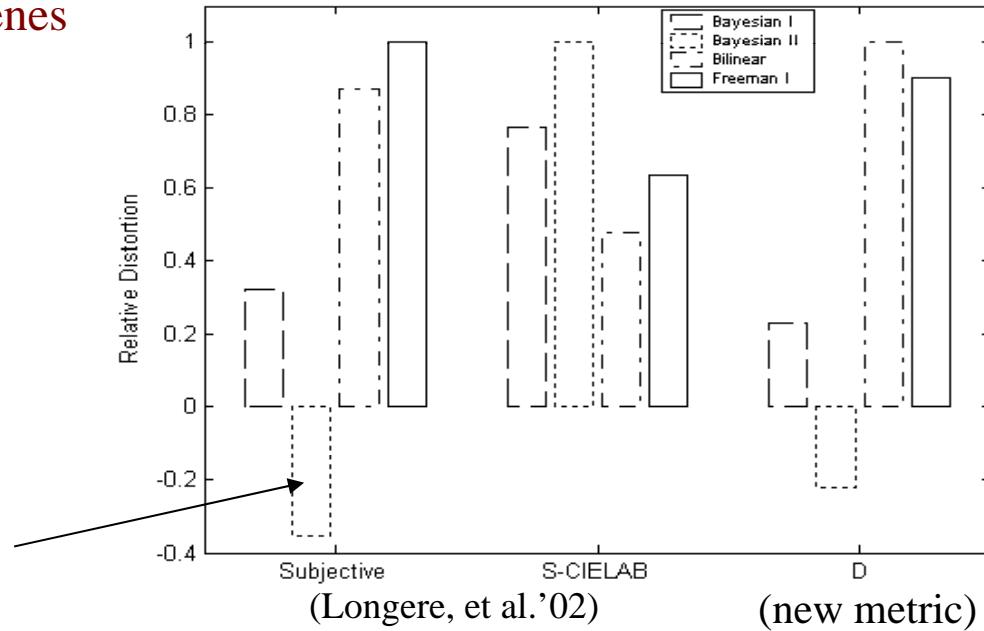
Lin, et al. '05

- D reduces to the mean absolute error (*MAE*) measure, if
  - JND is constant
  - different contrast changes are not differentiated

“...to tell a good picture from a good one...”

- Database with demosaiced image
- 50 images
- 1524x1012 scenes
- 9 subjects

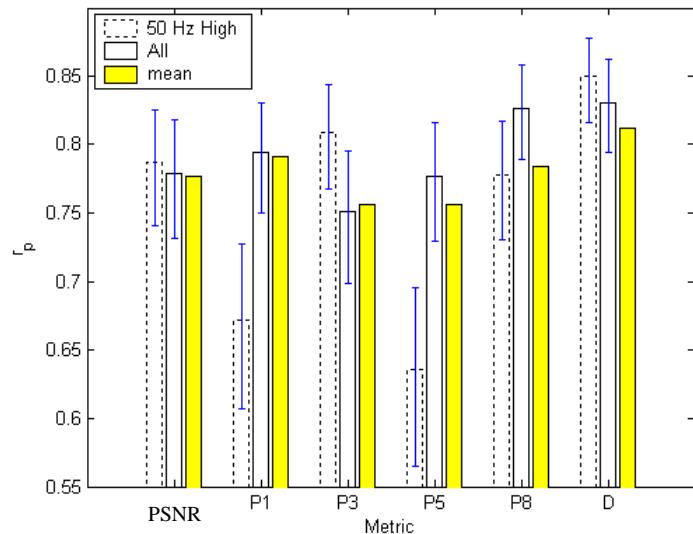
Better quality than  
the original image  
(due to [edge  
sharpening](#))



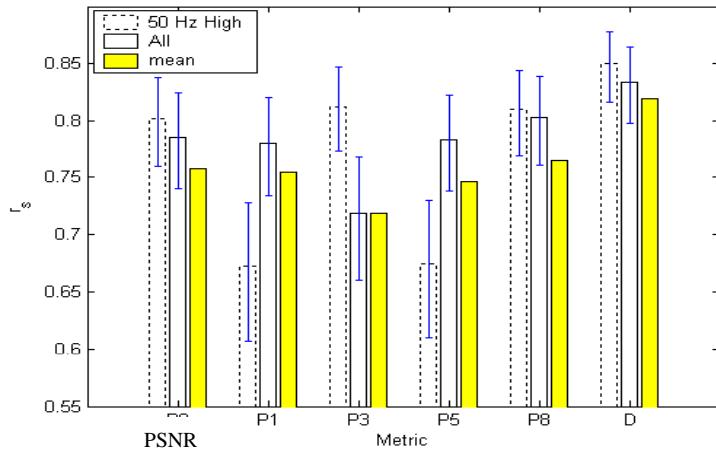
# Further Test Results

(with VQEG-I Data)

Pearson correlation (for accuracy)

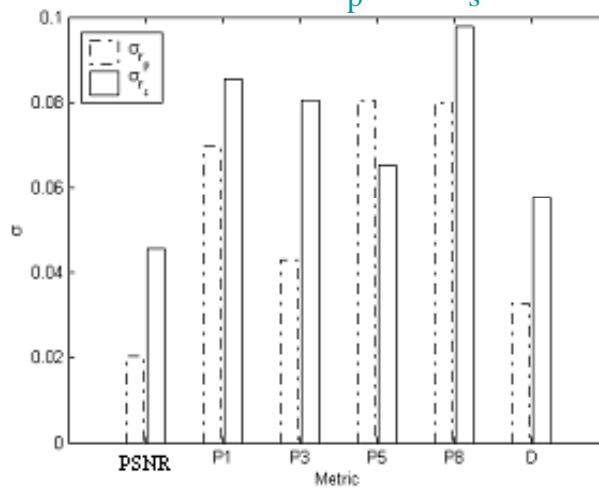


Spearman correlation (for order)

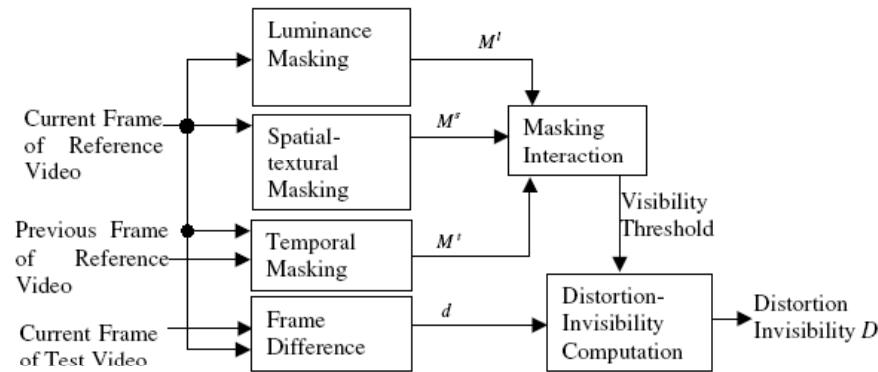
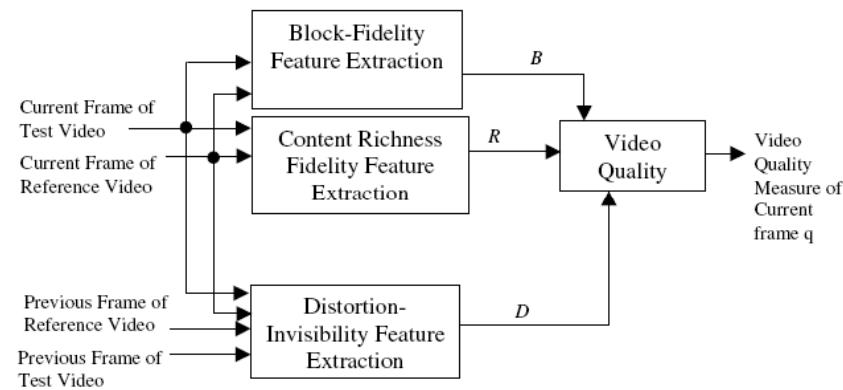


- 320 compressed video sequences
- Both PAL and NTSC format
- Different codecs
- 768 kb/s to 50 Mb/s
- Subjective viewing by independent labs
- P1,3,5,8: best performing metrics in VQEG-I

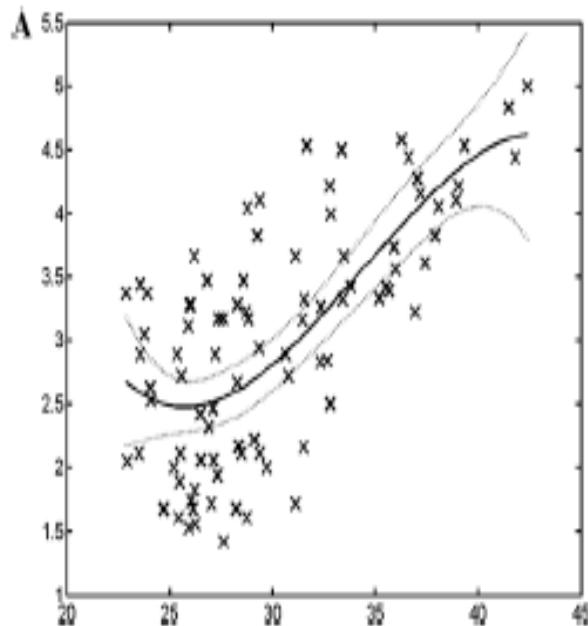
Variance of  $r_p$  and  $r_s$



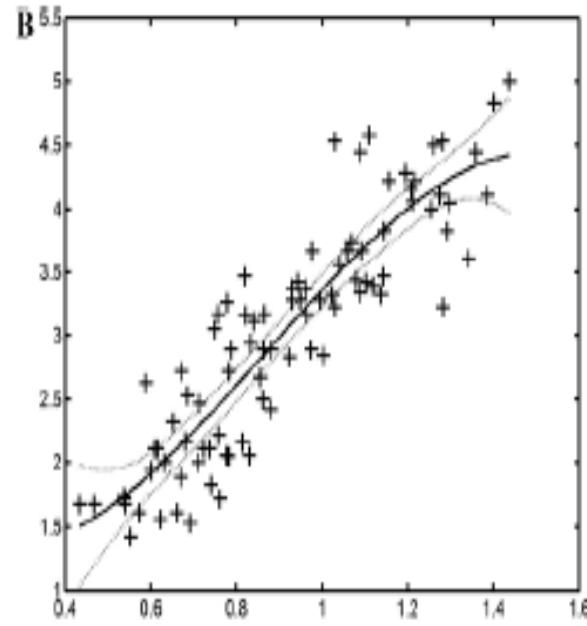
# JND-adjusted perceptual visual metric (PVM) for H.264 coded video



## Quality evaluation for H.264 coded video (performance)



MOS ~ PSNR

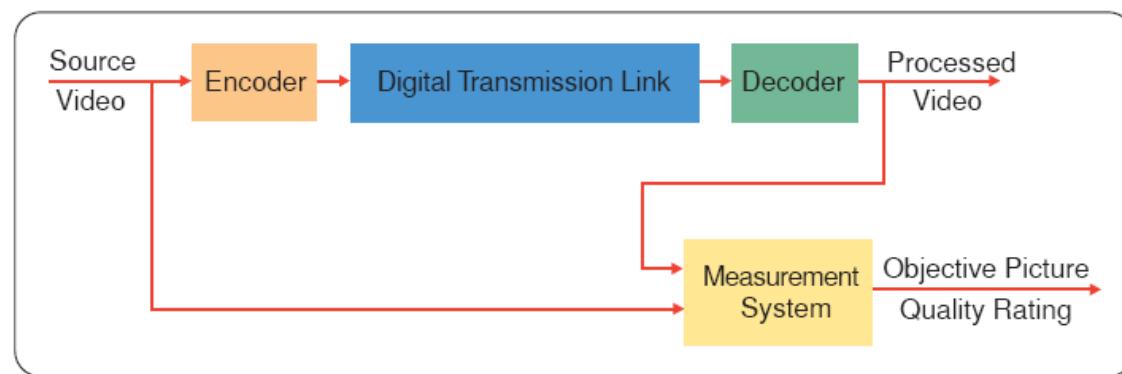
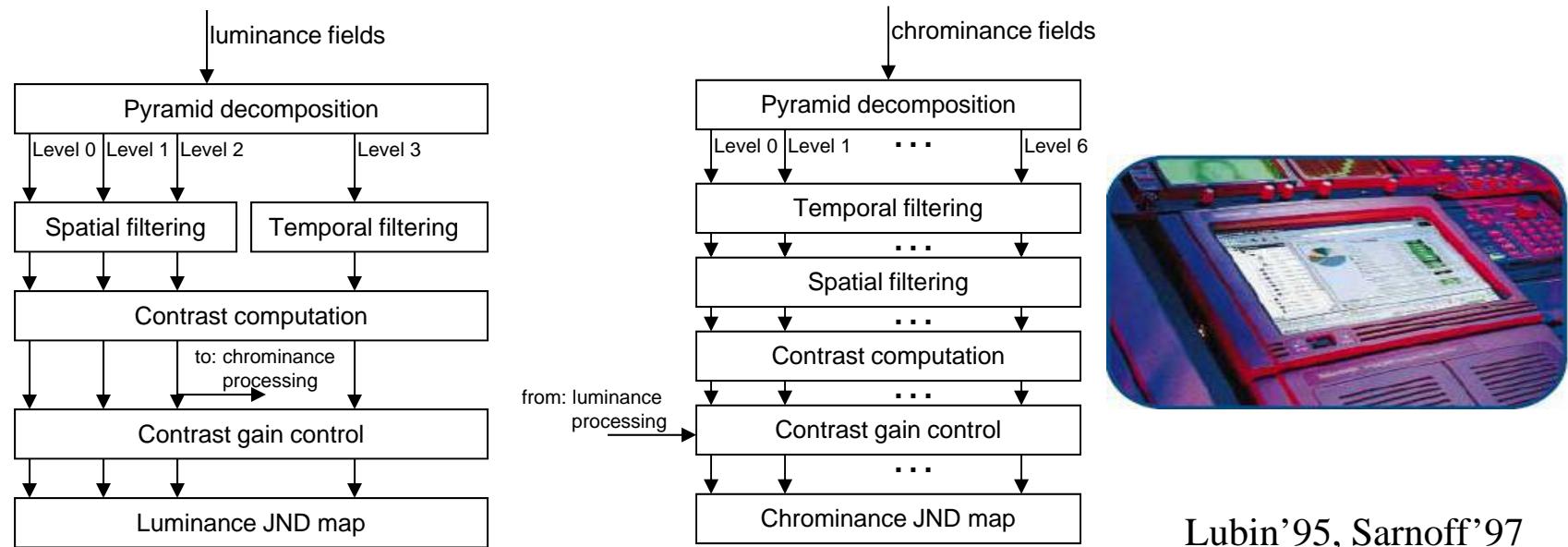


MOS ~ PVM

(Ong, et al.'06, JVCIR)

*To make the machine perceive as we do ...*

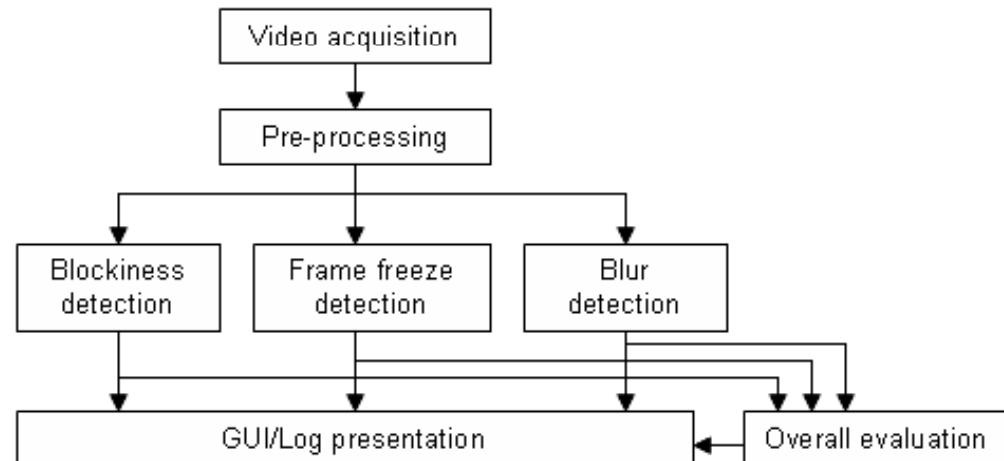
# Deployment for commercial products: Sarnoff's JNDmetrix<sup>TM</sup>: Tektronix's PQA200/500



# Industrial Deployment

# Visual Quality Monitoring System

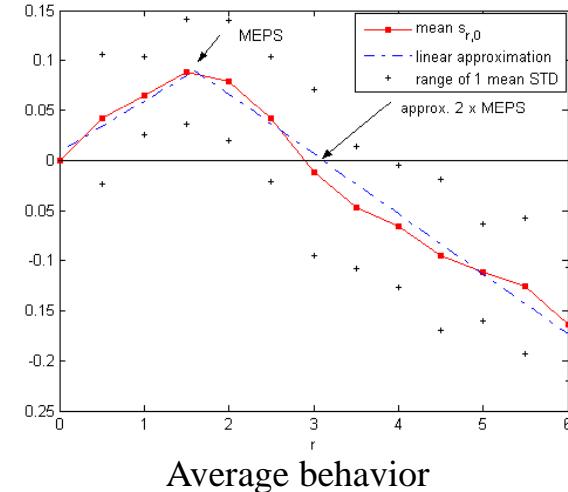
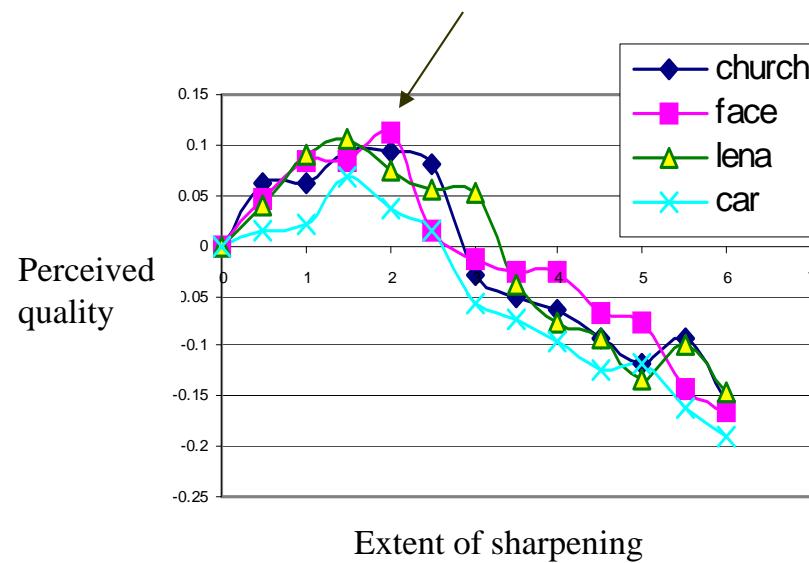
- in-service testing for mobile devices
  - PDAs
  - handphones
- in conjunction with a channel simulator



# Most Eye-pleasing Edge Sharpness (MEPS)

- edge sharpening:  $c^+_{e}$  increases
- optimal edge contrast  $\sim 2.6$  JND
- less *ad hoc* approach

most eye-pleasing;  
right-shifted if  $c^+_{ne}$  also increases

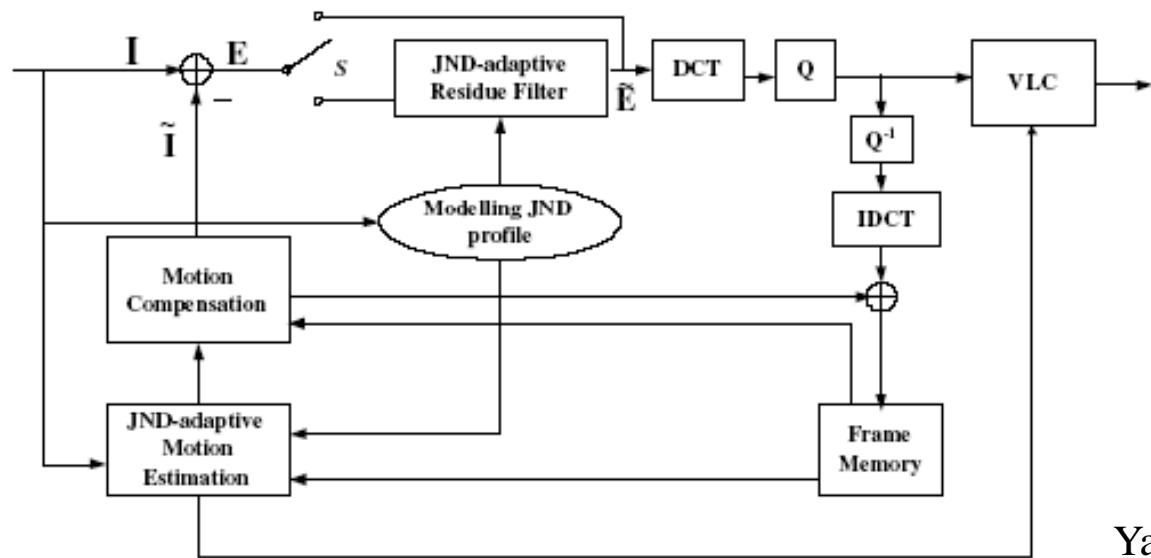


## Control of quantization in compression

$q = 2 \times JND \rightarrow$  maximum error < JND

Hontsch & Karam'02; Zhang, et. al.'05

# Perceptual Motion Estimation and Residue Handling



Yang, et al'05

Motion search: pruned when difference < JND  
Residues: discarded when they < JND

Video sequence	PSAD matching metric			PSAPD matching metric		
	Search points per MV	Recursions per match	CPU time (s)	Search points per MV	Recursions per match	CPU time (s)
Harp	921.17	134.90	3.72	882.49	83.87	2.71
Barcelona	921.12	75.00	1.99	916.91	50.57	1.81
Mobile & calender	921.15	72.97	1.91	862.81	61.70	1.80
Autumn leaves	916.07	68.01	1.27	889.89	43.04	1.02
Football	916.17	148.14	2.77	897.21	104.48	2.59
Sailboat	916.08	68.81	1.34	800.29	63.72	1.00
Susie	916.10	102.61	2.19	862.26	59.30	1.46
Tempete	916.10	89.47	2.19	846.60	74.49	1.72
Average	917.99	94.99	2.12	869.81	70.15	1.76
Average improvement with the PSAPD metric (%)				5.5	27.3	18.6

Video sequence	TM5		PVC	
	PSNR (dB)	PSPNR (dB)	PSNR (dB)	PSPNR (dB)
Harp	31.12	36.55	31.48	37.38
Barcelona	28.95	33.06	29.30	33.67
Mobile & calender	27.97	32.16	28.13	32.60
Autumn leaves	36.53	44.78	36.64	45.23
Football	32.24	36.97	32.25	37.21
Sailboat	34.68	44.12	34.85	44.97
Susie	40.60	52.25	40.82	52.88
Tempete	31.12	37.42	31.20	38.15
Average over 8 Seq.	32.91	39.66	33.08	40.26
Average improvement for PVC (dB)	0.17	0.60		

*“...killing 3 birds with 1 stone”*

- ✓ higher speed
- ✓ higher perceived quality
- ✓ higher PSNR

# Foveation-based Video Coding

- visibility threshold
  - as a function of spatial frequency  $f$  and retinal eccentricity  $e_c$ :

$$T_{f,e_c} = T_0 \exp\left(\alpha_0 f \frac{e_c + c}{c}\right)$$

Constants:  $T_0$ ,  $\alpha_0$  and  $c$

Wang, et al.'03

# Perceptually-driven rate control for videophone

Traditional rate control in videophone:

- Problem:

- ❖ Poorer quality for foreground-objects

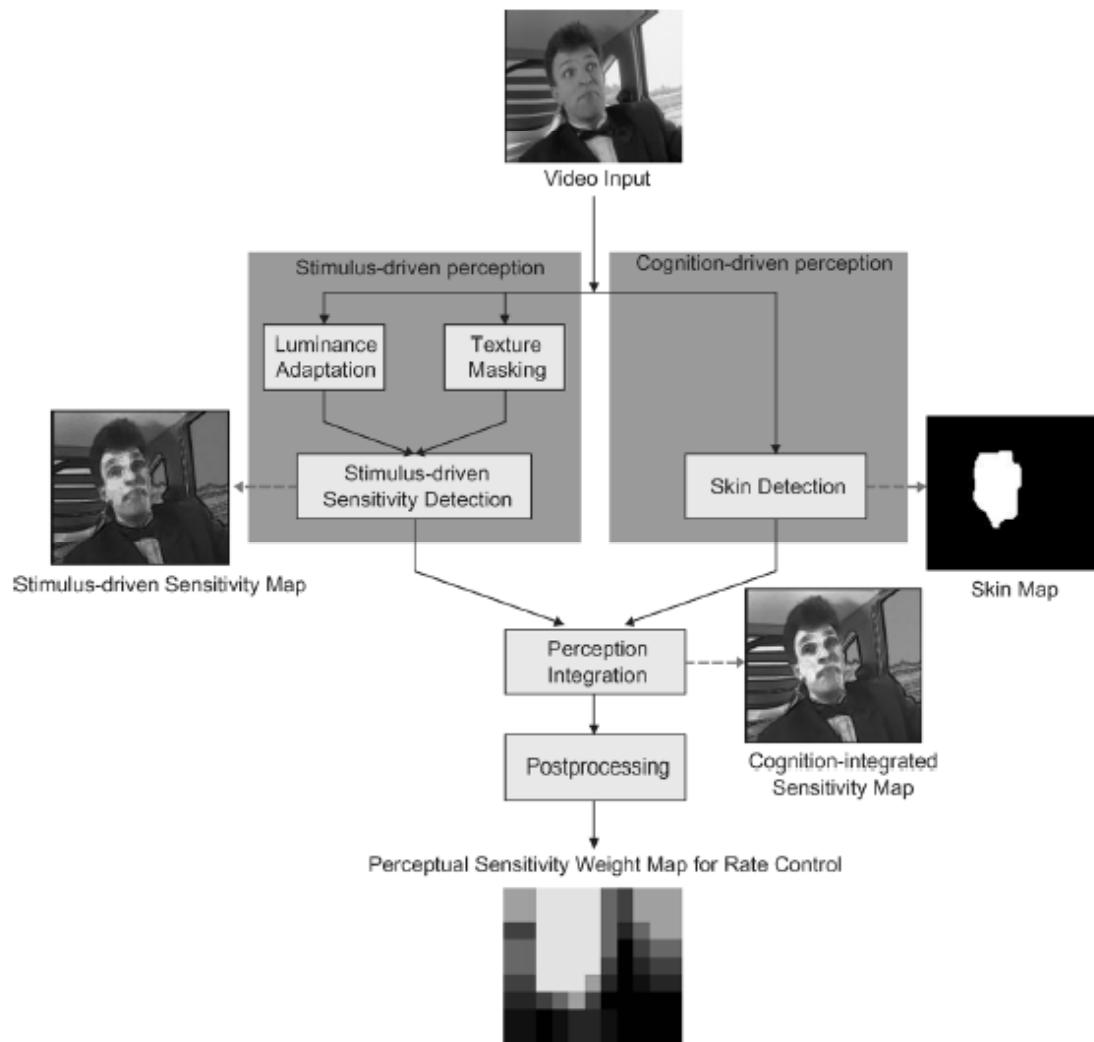
- Reason:

- ❖ Nonrigid deformation
  - ❖ More complex motion (e.g., rotation)

- Solution:

- ❖ Unequal bit allocation
  - ❖ Use of VA-modulated JND model

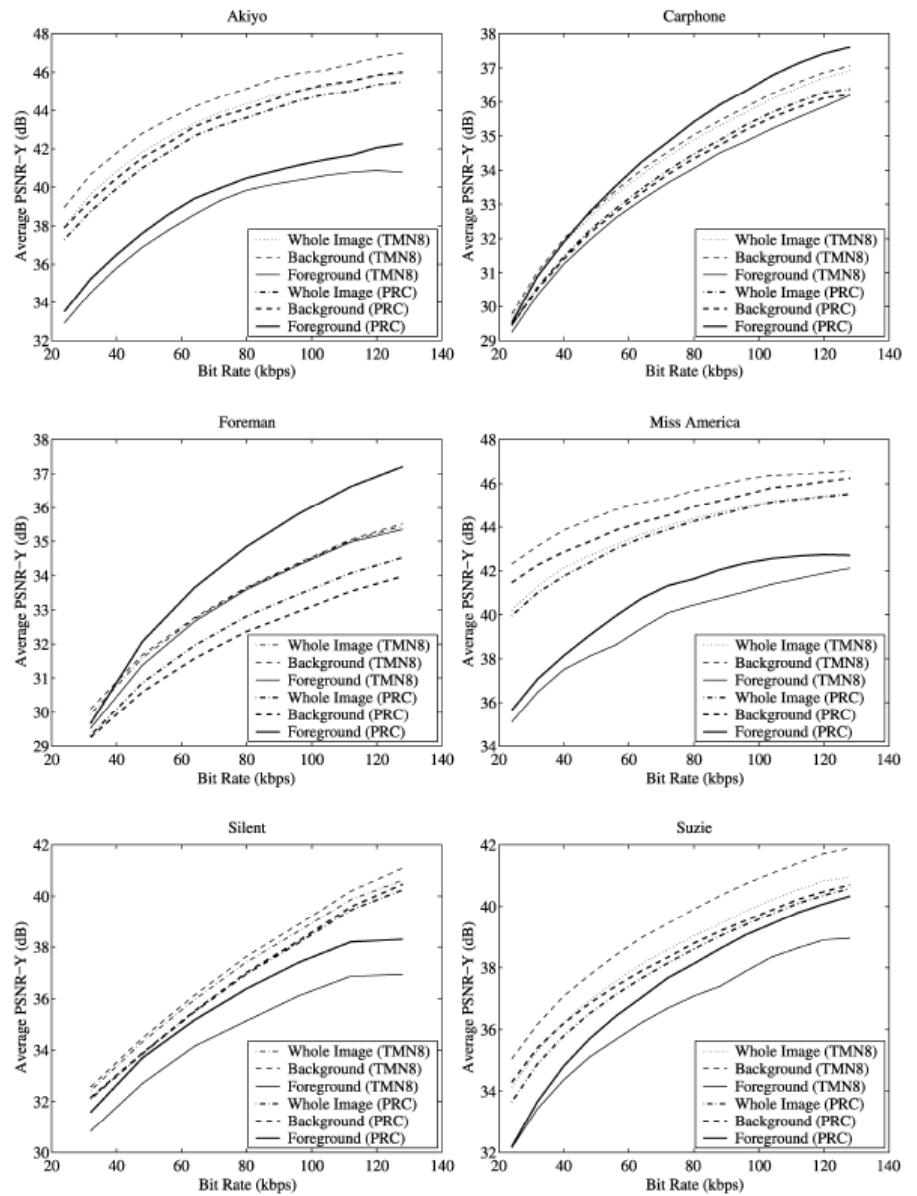
# Simplified VA-modulated JND



Yang, et al'05

# Coding Quality Improvement

Sequences	Total frames in the sequence	Bitrate (kbps)	no. of skipped frames		DMOS	
			TMN8	PRC	TMN8	Difference with PRC
<i>Akiyo</i>	300	24	6	6	45.2	-9.4
		48	2	2	27	-12
<i>Carphone</i>	350	64	1	1	64	-17
		96	0	0	48	-15
<i>Foreman</i>	400	64	1	1	70	-15
		96	0	0	51	-18.4
<i>Miss America</i>	150	24	2	2	46	-17
		48	0	0	30	-13
<i>Silent</i>	400	48	2	2	52	-6
		64	1	1	40	-9
<i>Suzie</i>	150	48	1	1	68	-7
		64	0	0	52	-9
Mean DMOS difference between PRC and TMN8 for all sequence			-12.3			



# Applications to computer graphics

- computer graphics: actively developing areas (interactive media)
- computational complexity

“The goal of computer graphics isn’t to control light, but to control our **perception** of it. Light is merely a carrier of the information we gather by perception.”

*J. Tumblin and J. A. Ferwerda, 2001*

# Image rendering



32 samples/pixel



64 samples/pixel

Bolin and Meyer (1998) applied Daly's visual difference predictor in rendering: two continuous intermediate images are compared to see which regions need more samples.

areas with less attention



# Perceptual computer graphics

- **Global illumination** --Ramasubramanian, et. al.'99
  - Pixel-based JND model (CSF, contrast masking)
  - Indirect illumination calculation
  - Computation stops when the difference < JND
- **Image rendering**
  - Ray tracing--Farrugia, *et al.*'04
  - Perceptual difference: for decision of subdivision
- **Compression on animation**
  - Visual attention model— simplified version of Itti'98 model
  - Saliency based MPEG-4 compression— Mantiuk, et al.'03

# Outline of Tutorial

- Introduction
- Relevant physiological & psychological phenomena
- Basic Computational Modules
- Perceptual Visual Processing & Applications
- Concluding Remarks, Further Discussion & Possible Future Work
- List of Most Relevant References (for further reading)

# *Summary*

- Various perceptual models developed
- Major considerations
  - luminance adaptation
  - spatio-temporal contrast sensitivity function
  - eye movement
  - visual attention
  - intra- & inter- band contrast masking
- Applications demonstrated
  - picture quality gauge
  - image/video compression
  - multimedia communication
  - computer graphics
- Industrial deployment
  - although technology still in its infancy
  - more companies buying the idea than 5 years ago

## Benefits of perceptual modeling

- Filling the gap in current technology:  
*“customer oriented”*
- New dimension of improvement in many visual processing tasks
  - room for further improvement with existing technology: *diminishing*
- Differentiating factor for commercial products

# *Possible further work:*

- **temporal effects**  
relatively less investigated
- **chrominance effects**  
esp. for non-coding distortion
- **joint modeling with other media**  
audio, text, and so on
- **mobile comm applications**  
application-specific
- **adaptive watermarking**
  - authentication
  - error resilience
- **streaming, transmission & networking**
  - priority labeling
  - resource allocation
  - global optimal solution
  - pricing system
- **computer graphics**
  - illumination calculation
  - image rendering
  - model/graphics compression
- **other possibilities**
  - medical images (e.g., TeleHealth)
  - e-learning
  - computational photography

# Emerging new forms of visual signal

- HD (high-definition) TV



- 3D TV (w/i & w/o goggles)



## **Relevant sources of information:**

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# **Asia-Pacific Signal and Information Processing Association (APSIPA)**

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**Thank you for your time !**

**Questions?**