# COLOR IMAGE PROCESSING FROM THE PHYSICAL, PSYCHOLOGICAL, AND BIOLOGICAL VIEWPOINTS

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MVA2015

## DEVELOPMENT OF COLOR IMAGE PROCESSING

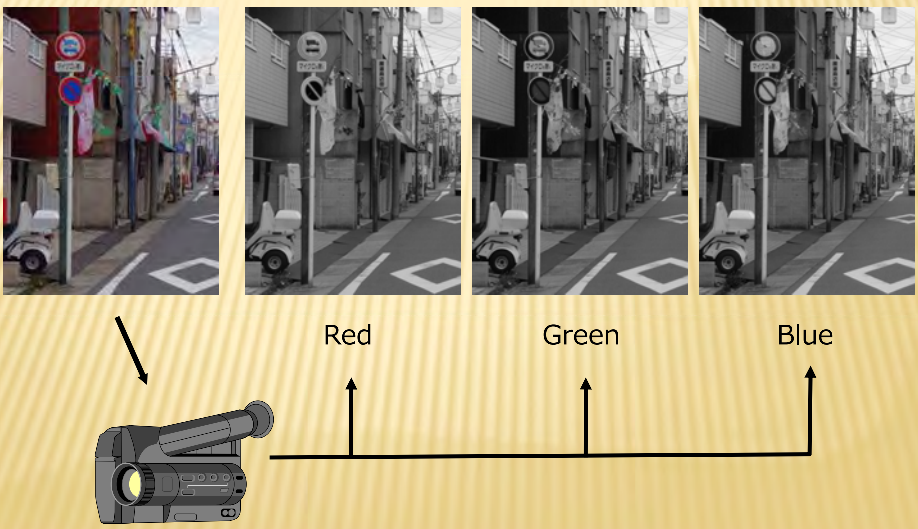
- Color image analysis
- Color reproduction
- Barrier-free/Universal design

- Color Image Analysis
  - Visual inspection
  - Robot vision
  - Remote sensing
  - ……

Physical Viewpoint

Multispectral Information

## COLOR IMAGE ANALYSIS (PHYSICAL)



## SALIENT COLOR EXTRACTION



Original | 140 colors | 41 colors

Color reduction

- Color Reproduction
  - Graphic arts
  - Photography
  - Illumination
  - Cosmetics

**Human Color Perception**

**Psychological Viewpoint**

## COLOR REPRODUCTION (PSYCHOPHYSICAL)

'Color' is highly human- specific attribute.

## HUMAN VISUAL INFORMATION PROCESSING

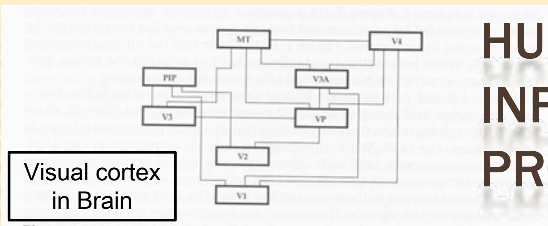
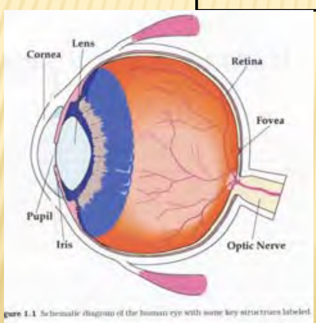
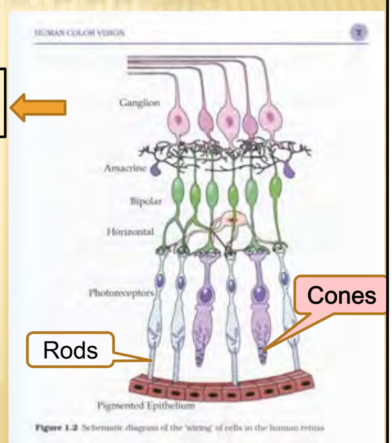



Figure 1.11 Partial flow diagram to illustrate the many streams of visual information processing in the visual cortex. Information can flow in both directions along each connection

Visual cortex in Brain

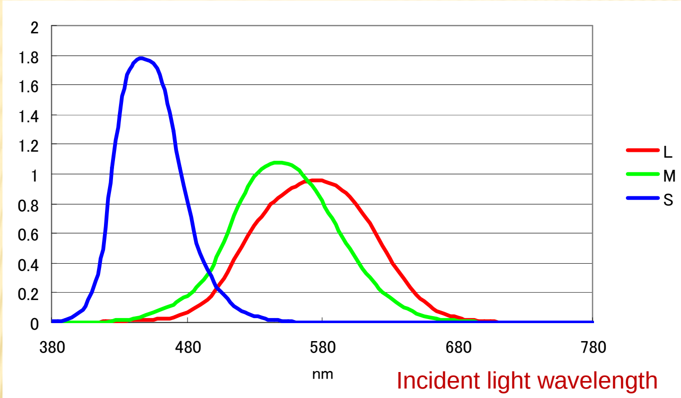
Lateral geniculate nucleus




From the book "Color Appearance Models" by Fairchild (Wiley)

## CONE SENSITIVITIES




Hunt-Pointer-Esteves

Tristimulus values

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 1.91019 & 1.11214 & 0.20195 \\ 0.37095 & 0.62905 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} L \\ M \\ S \end{pmatrix} \qquad \begin{pmatrix} L \\ M \\ S \end{pmatrix} = \int I(\lambda) \begin{pmatrix} \bar{l}(\lambda) \\ \bar{m}(\lambda) \\ \bar{s}(\lambda) \end{pmatrix} d\lambda$$

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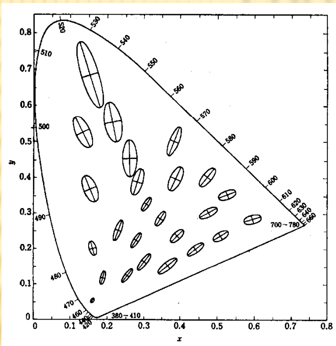
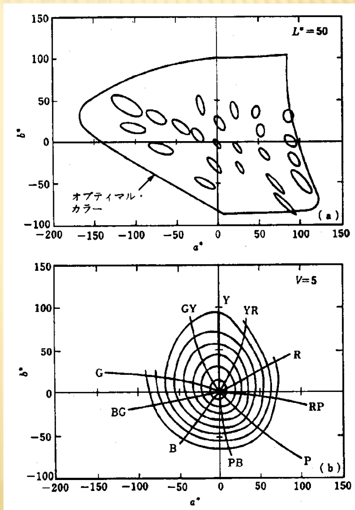
## UNIFORM COLOR SPACE BASED ON COLOR DIFFERENCE






$$\begin{cases} L^* = 116(Y/Y_n)^{1/3} - 16 \\ a^* = 500\left[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}\right] \\ b^* = 200\left[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}\right] \end{cases}$$

**Color difference**

$$\Delta E_{ab} = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$

**$\Delta E_{ab} \leq 3$ is a target.**

## DEVELOPMENT OF COLOR IMAGE PROCESSING

- Barrier-free or universal design
  - Processing for dichromats or anomalous trichromats
- Variety of color perception caused by genetic polymorphism
  - Processing for analyze human color perception

Human Color Perception

Biological Viewpoint

## TODAY'S TOPICS

- SOCS
  - Object spectra database for color sensor evaluation
- Illumination chromaticity estimation
  - Basis for computational color constancy & corresponding color reproduction
- Relation between color perception and genetic polymorphism
  - New research field from the biological viewpoint

# SOCS

## STANDARD OBJECT COLOUR SPECTRA DATABASE

~FOR COLOUR REPRODUCTION EVALUATION~

ISO/TR 16066 (2003)

- Spectral reflectance/transmittances of almost all visible objects are collected.
- Dimensions of the color distribution can be evaluated.
- Combining with illumination spectral data, every color appearance can be simulated.

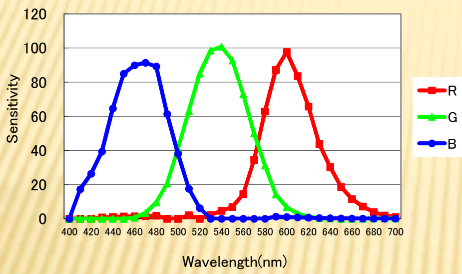
(Tajima, Color Imaging Conference (1998))

# MOTIVATION

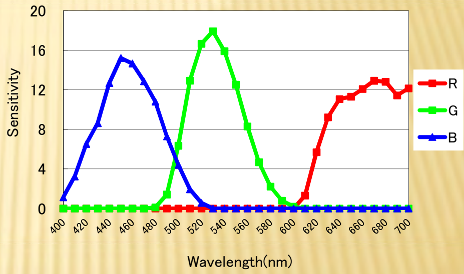
- **The Luther condition**
  - “To accurately r... rodu... c... r, each sensor must be a line... human cone sensitivitie...
- Good color reproducti... accomplished with sensors that do not satisfy the ’Luther condition’.
- What is the reason?

**However !**

CCD Camera sensor
ccdd50r




Graphic scanner sensor
swrd50



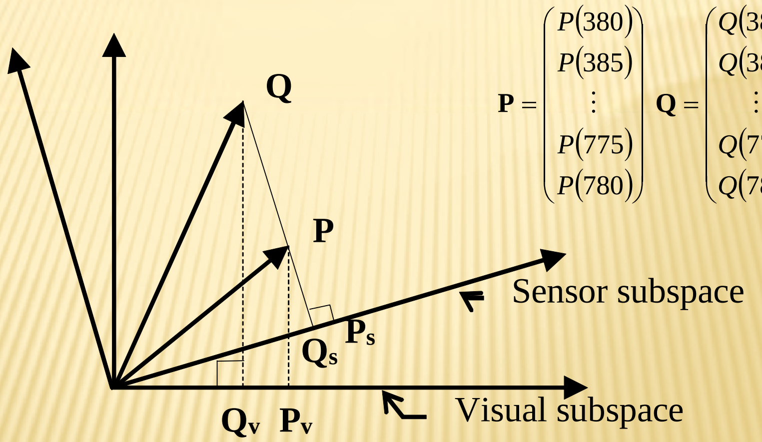

Neugebauer's quality factors

$q_r$=0.95
$q_g$=0.98
$q_b$=0.85

$q_r$=0.11
$q_g$=0.90
$q_b$=0.95

# LUTHER CONDITION

$$\mathbf{P} = \begin{pmatrix} P(380) \\ P(385) \\ \vdots \\ P(775) \\ P(780) \end{pmatrix} \quad \mathbf{Q} = \begin{pmatrix} Q(380) \\ Q(385) \\ \vdots \\ Q(775) \\ Q(780) \end{pmatrix}$$



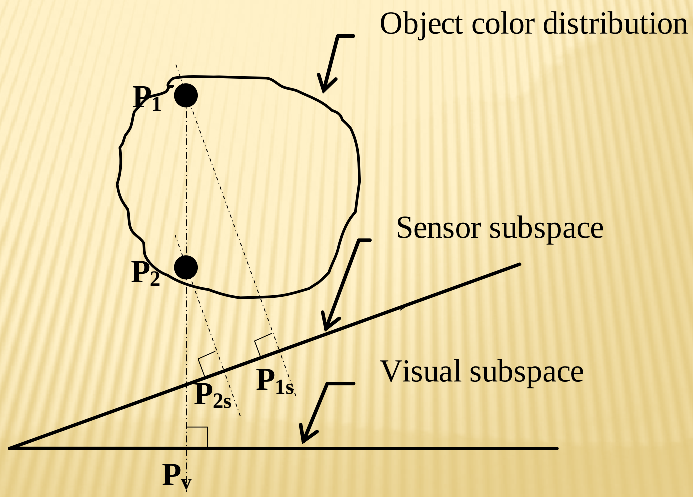

**The visual subspace is the space, which is spanned by the cone sensitivities.**

## MATRIX COLOR CORRECTION

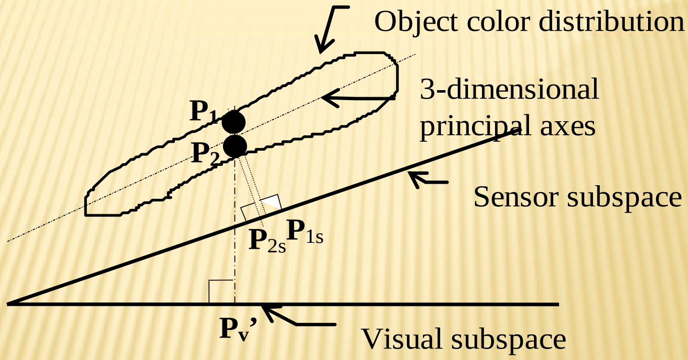
- Good color reproduction is often obtained by a simple matrix color correction.

$$\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

## COLOR APPEARANCE OF WIDE COLOR DISTRIBUTION



## COLOR APPEARANCE OF THIN COLOR DISTRIBUTION

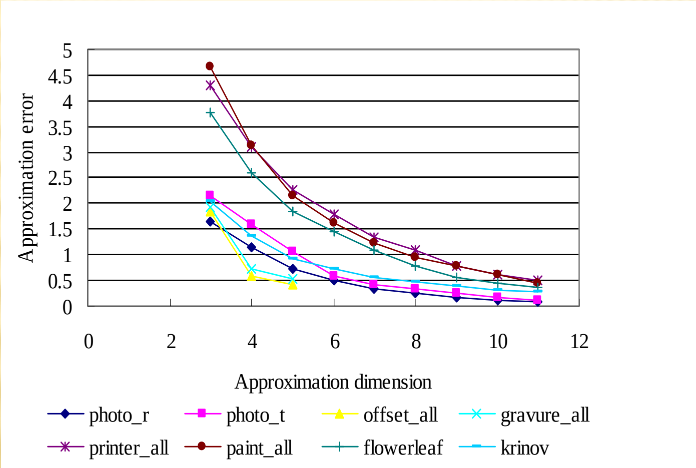



**The re-projection procedure can be expressed by the 3×3 matrix.**

## TOTAL NUMBER OF COLLECTED SPECTRAL DATA FOR SOCS (ISO/TR 16066)

| Category | No. of sub-categories | No. of colors |
|---|---|---|
| Photographic materials | 8 | 2,304 |
| Graphic printing (Offset / Gravure) | 33 | 30,624 |
| Color computer printers | 21 | 7,856 |
| Paint (for exterior / interior objects) | | 336 |
| Paints (for art) | 4 | 229 |
| Textiles | 6 | 2,832 |
| Flowers | | 148 |
| Leaves | | 92 |
| Human skin | | 8,570 |
| Krinov data (natural objects) | | 370 |
| Total | | 53,361 |

## ERROR VS. APPROXIMATION DIMENSIONS




## LEGENDS VERIFIED BY SOCS

- Because the spectral transmittance of color slides and the spectral reflectance of lithographic prints, which constitute the most of print material, can be sufficiently approximated by three principal components, the conventional scanners, whose source images are mostly from those, do not need to satisfy the Luther condition.

**These were empirically known but experimentally verified using SOCS.**

## KNOWLEDGE OBTAINED USING SOCS

- Spectral reflectance restoration quality after the linear compensation is closely related to the subspace dimensions that the spectral reflectances span.
- Normally, 6 dimensions are sufficient to restore the object spectra.

## SOCS IS MORE IMPORTANT FOR ARTIFICIAL ILLUMINATION EVALUATION

(Photo excluded)

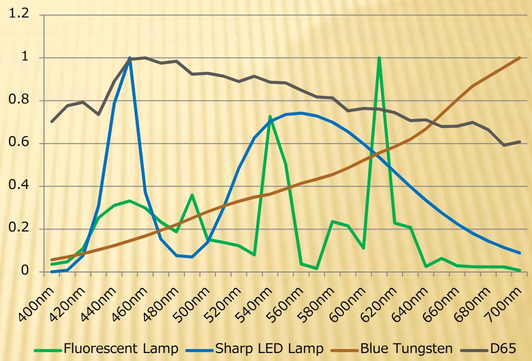
Nuclear reactors exploded

March 2011

(Photo excluded)

Nobel prize for blue LED development

December 2014



## SOCS SHOULD BE CONTINUALLY DEVELOPED

- Add animal and fruits color data.
- More inkjet printer data.
- Data of fluorescent materials
  - In papers
  - In inks

## TODAY'S TOPICS

- SOCS
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- Illumination chromaticity estimation
  - Basis for computational color constancy & corresponding color reproduction
- Relation between color perception and genetic polymorphism
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## COMPUTATIONAL COLOR CONSTANCY & CORRESPONDING COLOR REPRODUCTION

- Computational color constancy
  - Restore the scene color under the standard illumination from the scene color under the actual unknown illumination.
- Corresponding color reproduction
  - Reproduce the scene colors that we perceive under different illuminations.

## COMPUTATIONAL COLOR CONSTANCY

Under illuminant A

Under illuminant D65

The image restored from the image under illuminant A

**Illumination estimation from the input image is necessary!**

## CORRESPONDING COLOR REPRODUCTION

Under illuminant A

Under illuminant D65

The image under D40 llumination simulated from that under illuminant A

**Illumination estimation from the input image is necessary!**

## CUES FOR ILLUMINATION ESTIMATION

- Gray world assumption
  - Scene average color be gray.
- Color by correlation
  - Scene color gamut be consistent with illumination gamut.
- Dichromatic reflection model
  - Reflection property of non-metallic objects.

Mankind uses many cues depending on the situation.

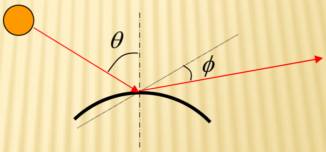
## DICHROMATIC REFLECTION MODEL (DRM)
### ~PHYSICAL MODEL~

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \alpha \begin{pmatrix} R_o \\ G_o \\ B_o \end{pmatrix} + \beta \begin{pmatrix} R_w \\ G_w \\ B_w \end{pmatrix}$$

$\begin{pmatrix} R_o \\ G_o \\ B_o \end{pmatrix}$ Color of Diffuse Reflection (Object Color)

$\begin{pmatrix} R_w \\ G_w \\ B_w \end{pmatrix}$ Color of Specular Reflection (Illumination Color)

Surface colors are distributed on the plane that the object color vector and the illumination color vector spans. (Shafer 1985)




Phong's Reflectin Model

$\alpha = \cos\theta, \quad \beta = \cos^n \phi$

Torrance – Sparrow's Model

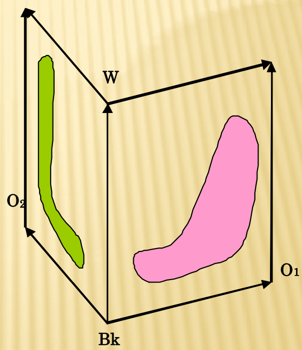
$\alpha = \cos\theta, \quad \beta = \dfrac{1}{\cos\theta_{s1}} e^{\frac{-\theta_{s2}}{2\sigma^2}}$

θs1: Angle between the illumination direction and the surface normal.

θs2: Angle between the middle of the illumination direction and the viewing direction, and the surface normal.

## ILLUMINATION COLOR ESTIMATION BASED ON THE DRM

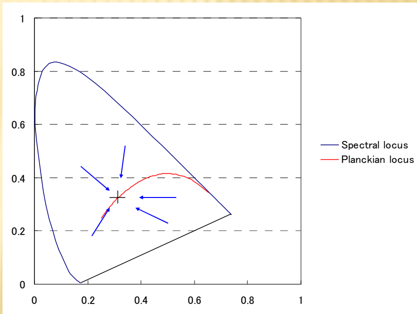
- If there are multiple surface colors, the common line of the distribution plane correspond to the illumination color.



# ILLUMINATION CHROMATICITY ESTIMATION BASED ON THE DRM

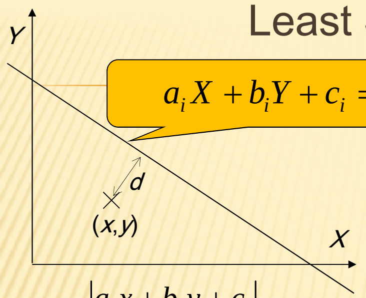
The chromaticity of the mixture of object color and illumination color is on the straight line that connects the chromaticities of the two colors $(x_o, y_o)^t$ and $(x_w, y_w)^t$ on the chromaticity diagram.

If there are many color regions, The chromaticity of the reflected light is distributed on the straight lines that are oriented toward the illumination chromaticity.




The illumination chromaticity is at the cross point of the distribution lines!!

# Least Squares Method




$$F(x, y) = \sum_i w_i d_i^2$$

The function to be minimized

$w_i$: Weight of the area

$$d_i = \frac{|a_i x + b_i y + c_i|}{\sqrt{a_i^2 + b_i^2}}$$

$$\begin{cases} \dfrac{\partial F(x,y)}{\partial x} = 0 \\ \dfrac{\partial F(x,y)}{\partial y} = 0 \end{cases}$$

$$\Rightarrow \quad x = \frac{\begin{vmatrix} -\sum_i \frac{w_i a_i c_i}{a_i^2 + b_i^2} & \sum_i \frac{w_i a_i b_i}{a_i^2 + b_i^2} \\ -\sum_i \frac{w_i b_i c_i}{a_i^2 + b_i^2} & \sum_i \frac{w_i b_i^2}{a_i^2 + b_i^2} \end{vmatrix}}{\begin{vmatrix} \sum_i \frac{w_i a_i^2}{a_i^2 + b_i^2} & \sum_i \frac{w_i a_i b_i}{a_i^2 + b_i^2} \\ \sum_i \frac{w_i a_i b_i}{a_i^2 + b_i^2} & \sum_i \frac{w_i b_i^2}{a_i^2 + b_i^2} \end{vmatrix}}, \quad y = \frac{\begin{vmatrix} \sum_i \frac{w_i a_i^2}{a_i^2 + b_i^2} & -\sum_i \frac{w_i a_i c_i}{a_i^2 + b_i^2} \\ \sum_i \frac{w_i a_i b_i}{a_i^2 + b_i^2} & -\sum_i \frac{w_i b_i c_i}{a_i^2 + b_i^2} \end{vmatrix}}{\begin{vmatrix} \sum_i \frac{w_i a_i^2}{a_i^2 + b_i^2} & \sum_i \frac{w_i a_i b_i}{a_i^2 + b_i^2} \\ \sum_i \frac{w_i a_i b_i}{a_i^2 + b_i^2} & \sum_i \frac{w_i b_i^2}{a_i^2 + b_i^2} \end{vmatrix}}$$

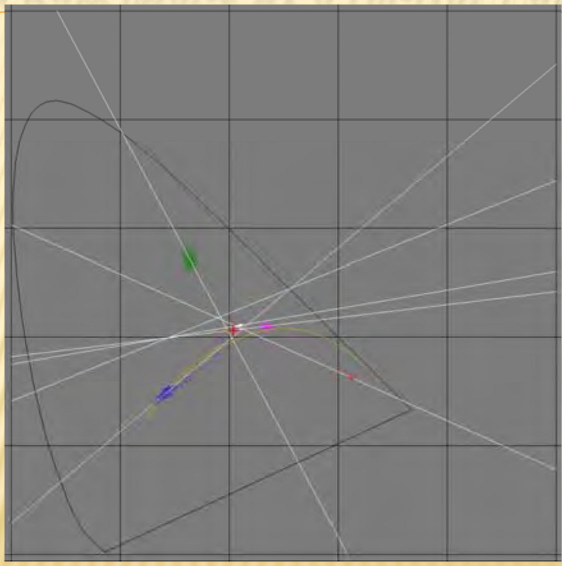
## CHROMATICITIES SAMPLED BY SPECTRO-RADIOMETER

## IF THE PROBLEMS SOLVED

A scene illuminated by illuminant A.

Manually segmented colored regions

## CHROMATICITIES SAMPLED FROM A RAW IMAGE BY A DIGITAL CAMERA



**Camera is neither a photometer nor a colorimeter.**

## PHOTOMETRIC CALIBRATION & ILLUMINATION ESTIMATION

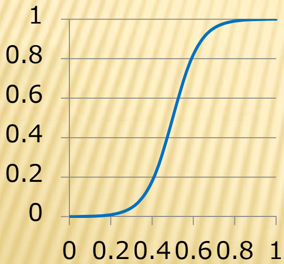
- Each channel of a 'Raw mode image' is an output of each (R, G or B) sensor.
- If each sensor transfer function $f_R, f_G$ or $f_B$ is linearly calibrated, chromaticities of the colored objects should be on straight lines, and the lines cross each other at the illumination chromaticity point.

$$R' = f_R(R), G' = f_G(G), B' = f_B(B)$$

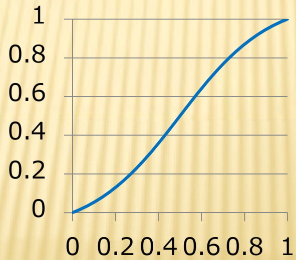
## CORRECTION WITH HYPERBOLIC FUNCTIONS

- Tone correction has been conventionally carried out with S-shaped function in photographic or graphical industries.

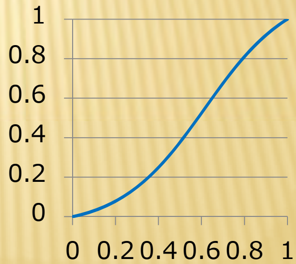
$$y = \frac{\rho}{2} \cdot \frac{e^{\alpha(2(x-\beta)-1)} - e^{-\alpha(2(x-\beta)-1)}}{e^{\alpha(2(x-\beta)-1)} + e^{-\alpha(2(x-\beta)-1)}} + \delta + \frac{1}{2}$$




ρ=1.001, δ=0




ρ=1.2, δ=0




ρ=1.2, δ=0.05

## PARAMETER OPTIMIZATION

- Two parameters ρ and δ are optimized so that
  - $F(x,y)$ be minimum: all distribution lines cross each other at a point.
  - Chromaticity of each colored region be distributed on a straight line.

$$F(x,y) = \sum_i w_i d_i^2$$

Optimized / Original

## SUMMARY ON ILLUMINATION ESTIMATION

- Possibility for simultaneous processing of sensor calibration and illumination estimation, based on dichromatic reflection model, is proposed.
  - More sophisticated sensor linearity calibration method should be the future work.

## PROBLEMS

- Homogeneity
  - Color of natural objects are not homogeneous.
  - **Artifacts/Natural objects s**

  (Tajima & Kono, IEICE Tans. (2008))

Not solved. But …

- Segment
  - Each c ject should be segmented.
  - **Application of color quantization.**

  (Tajima & Ikeda, J of IIEEJ (1989))

## COLOR QUANTIZATION

Full color representation

Representation by 33 colors

## TODAY'S TOPICS

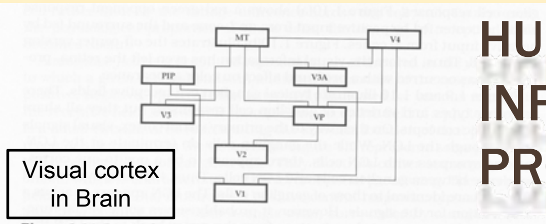
- SOCS
  - Object spectra database for color sensor evaluation
- Illumination chromaticity estimation
  - Basis for computational color constancy
- Relation between color perception and genetic polymorphism
  - New research field from the biological viewpoint

## BIOLOGICAL COLOR PERCEPTION

- Is color discrimination hereditary or acquired?
  - Whether you are trichromatic or dichromatic depends on genetic information.
  - How about the color information processing in the nerves and the brain?

(Tajima, Tanaka, Suzuki, Moriyama & Yoshida, Color, and Imaging Conf. (2013))

## HUMAN VISUAL INFORMATION PROCESSING

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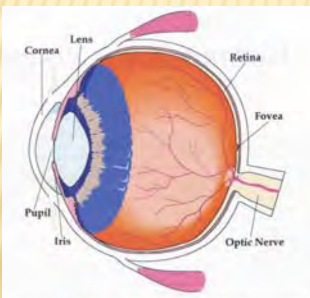
Lateral geniculate nucleus



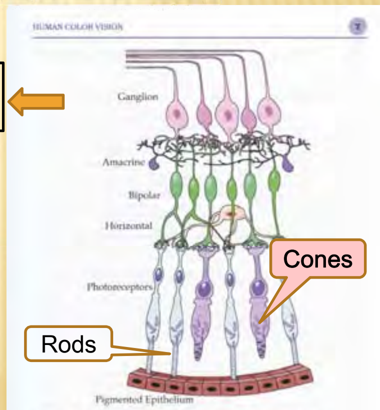
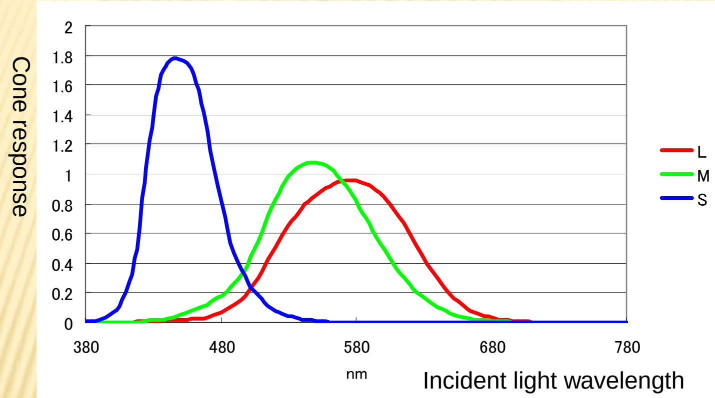




Figure 1.2 Schematic diagram of the 'wiring' of cells in the human retina

From the book "Color Appearance Models" by Fairchild (Wiley)

## CONE SENSITIVITIES

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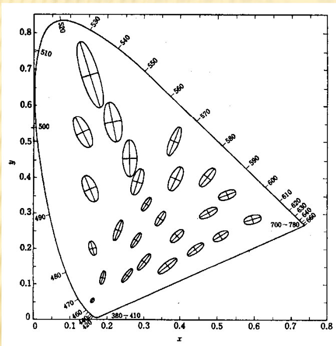
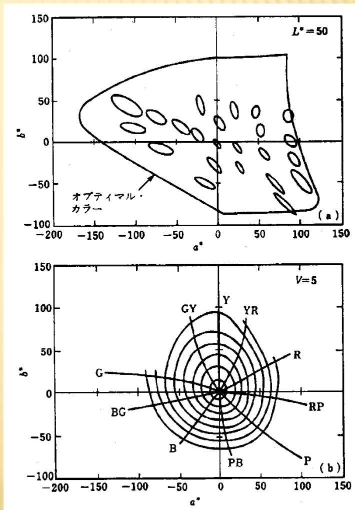
## NEURAL AND BRAIN INFORMATION PROCESSING, AND UNIFORM COLOR SPACE



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**Color difference**

$$\Delta E_{ab} = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$

**$\Delta E \gtrsim 0.5$ is sensible**

## INFORMATION PROCESSING FOR COLOR PERCEPTION

1. Three kinds of cones sense the spectral information.

⇩

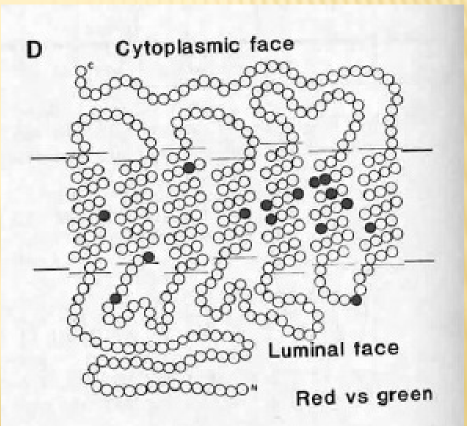
2. Color difference is perceived after the complicated processing in neurons and the brain.

Question

**How is color difference perceived by the persons who have cones with shifted spectral sensitivity ?**

## POLYMORPHISM IN L AND M CONE SENSITIVITY

- Genes for L and M cone opsins are on the X chromosome
- Both genes are very similar, and code 364 amino acid residues.
- Only 15 amino acid residues (black) are different from each other.




(Nathans et al., Science(1986))

## AMINO ACID RESIDUES THAT MAINLY CAUSE THE LIGHT ABSORPTION WAVELENGTH SHIFT FROM L OPSIN TO M OPSINS

~20% replaced in L

| Order of amino acid residue | L opsin | M opsin | Light absorption wavelength shift from L opsin to M opsin |
|---|---|---|---|
| 180th | Serine | Alanine | –7±1nm |
| 277th | Tyrosine | Phenyl-alanine | –9±1nm |
| 285th | Threonine | Alanine | –15±1nm |

(Asenjo et al., Neuron (1994))

## PURPOSE OF THIS STUDY

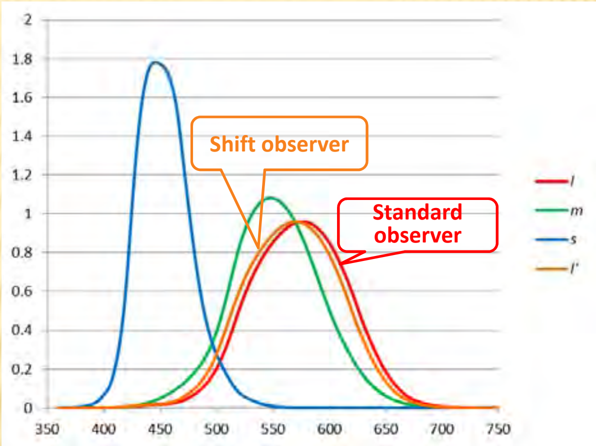
To investigate the relation between the polymorphism in L cone spectral sensitivity and color perception.

**[Assumption]**
Even if the cone sensitivity varies, the following information processing does not vary.

↓

Color difference calculation → Experiment on color discrimination ← DNA analysis on L opsin of normal color vision subjects

## CONE SENSITIVITIES WITH THE SHIFTED L CONE SENSITIVITY ($\bar{l}'$)




The shifted L cone sensitivity $\bar{l}'$ is generated by shifting the $\bar{l}$ of the standard observer by 6nm to the $\overline{m}$ direction.

## DESIGN OF THE COLOR DISCRIMINATION EXPERIMENT

We show the two very similar colors (color pairs) on a display (upper and lower sides).

↓

We prepared the color pairs so that the color difference for the **standard observer** is **larger** than that for the shift observer.

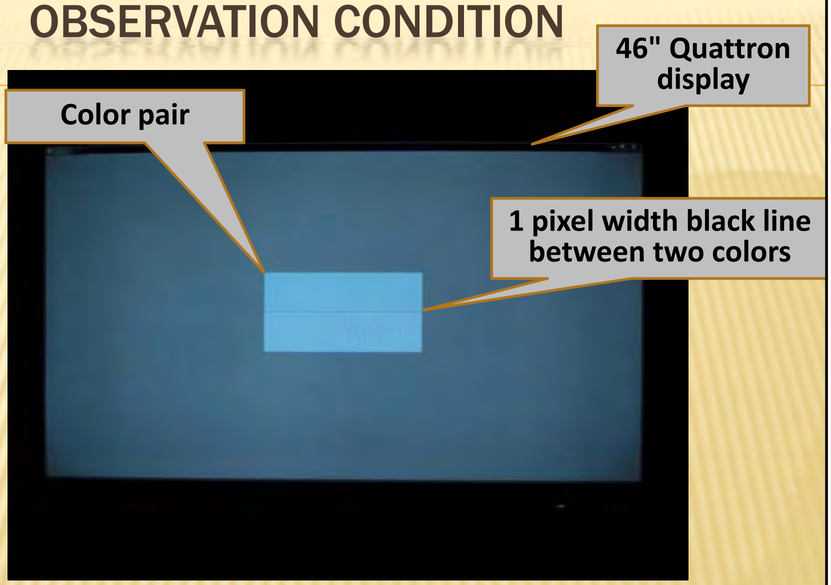
↓

Does the color discrimination conform to what is expected by the color difference calculation ?

To see the phenomenon clearly,

The difference between the observers in color difference was enhanced by **Quattron.**

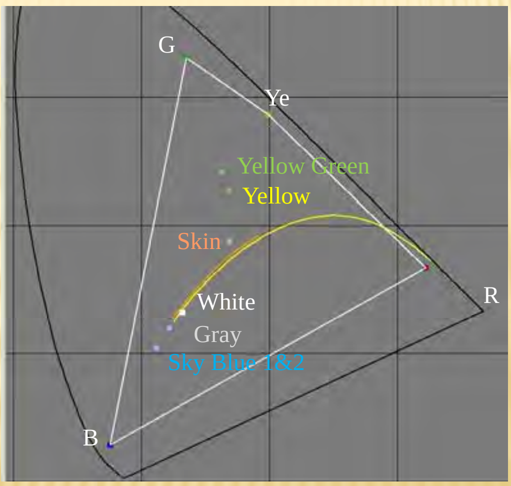
## OBSERVATION CONDITION




Reference white: 287cd/m$^2$
Color temperature: 14,000K

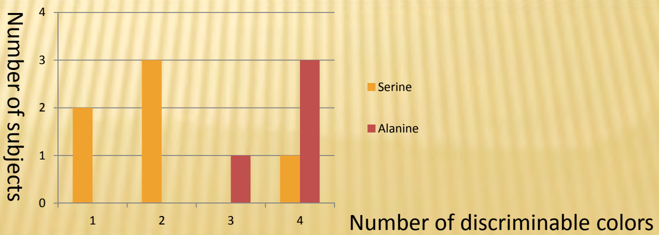
Surround: 20% Gray

## CHROMATICITIES OF THE COLOR PAIRS



# EXPERIMENTAL RESULT

| Subject | | 1 | 2 | 3 | 4 | 6 | 7 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gray | | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | × | ○ |
| Sky Blue 1 | | ○ | ○ | ○ | ○ | ○ | ○ | ○ | × | ○ | ○ |
| Yellow | | ○ | ○ | × | ○ | × | ○ | ○ | × | × | × |
| Yellow Green | | ○ | × | × | ○ | × | ○ | ○ | × | × | × |
| Skin | | × | × | × | × | × | × | × | × | × | × |
| Sky Blue 2 | | × | × | × | × | × | × | × | × | × | × |
| Number of discriminable color pairs | | 4 | 3 | 2 | 4 | 2 | 4 | 4 | 1 | 1 | 2 |
| L opsin amino acid residue | 180th | Ala | Ala | Ser | Ala | Ser | Ser | Ala | Ser | Ser | Ser |
| | 277th | Tyr | Tyr | Tyr | Tyr | Tyr | Tyr | Tyr | Tyr | Tyr | Tyr |
| | 285th | Thr | Thr | Thr | Thr | Thr | Thr | Thr | Thr | Thr | Thr |




# SUMMARY OF THE EXPERIMENT

- The subjects who could discriminate two or less color pairs were those, whose 180th amino acid residue was **serine**. (These subjects should be the standard observers.)
- Those, whose 180th amino acid residue was **alanine**, could discriminate three or more color pairs.

**Contrary to the assumption !**

## SUMMARY OF THIS TOPIC

- Color discriminability is dependent on whether the 180th amino acid residue of L opsin is serine or alanine.
- The experimental result is contrary to the expectation that the polymorphism influences only the cone sensitivity, and does not influence the neural or brain information processing.

⇩

- It is likely that the neural or brain processing grows differently, depending on the genetic cone sensitivity difference.
- It may cause the deformation of the uniform color space.

## REMAINING PROBLEMS

- The number of subjects is ten (small?)
  - More subjects are desirable.
- The number and color region of color pairs is limited.
  - More color pairs are desirable

### Interesting Questions

- How about females ?
- How does brain visual processing grow ?

**More detailed study is expected !**

## TODAY'S TOPICS

- SOCS
  - Object spectra database for color sensor evaluation
- Illumination chromaticity estimation
  - Basis for computational color constancy & corresponding color reproduction
- Relation between color perception and genetic polymorphism
  - New research field from the biological viewpoint

- There remains no interesting problem in color image processing/analysis.

- **There are many interesting topic on color image processing/analysis from various view points!**

***Thank you !***