

Stability of the color-opponent signals under changes of illuminant in natural scenes

J. Opt. Soc. Am. A

Vol. 22, No. 10, Oct. 2005

P.G.Lovell, D.J.Tolhurst, C.A.Parraga, R.Baddelay, U.Leonards,
J.Troscianko, and T.Troscianko

***School of Electrical Engineering and Computer Science
Kyungpook National Univ.***

Abstract

- ◆ Properties of opponent-channel response
 - Stability of spatial and temporal variation in illumination
 - Calculation : primate (luminance, RG , BY)
bird (luminance, RG)
 - Change in illumination
 - $RG > BY$ (primate)
 - Difference between species
 - Bird
 - Great separation L and M cone
 - Narrow bandwidth

Introduction

- ◆ Determination of spectrum of light reaching an observer's eye from an object
 - **Reflectance** of object's material : invariability
 - **Illuminant** : markedly varying intensity in time and space
- ◆ Primate (Human and monkey)
 - Constitution of three opponent channel
 - red-green (RG), blue-yellow (BY), light-dark (Lum)
 - Exploration
 - Sampling natural image containing real noise (shadows, specularities)
 - Considering change of light naturally in intensity

◆ Illuminant

- Illuminated and shadowed parts of an object
 - Difference only in the intensity of illumination
- Color of the natural illuminant \Rightarrow not constant
 - Varying over time course of a day
 - Change of weather
 - Light from cloudy sky vs direct sunlight
 - \hookrightarrow bluer

◆ Purpose

- Analysis of RG and BY opponent system
- Showing optimization of primate RG opponent system for detecting and differentiating edible objects

Methods

◆ Cameras and calibration

- Using uncompressed output
 - ⇒ Calculating cone response
 - Human : L, M, S
 - Starling : L, M
- Requirement of thorough characterization
 - Camera's nonlinear gamma function
 - Spectral activation function of R,G,B sensors
- Reason of camera characterization
 - Obtaining LMS cone from RGB pixel value for every point of scene

– Problems of RGB to LMS mapping

- Not exact transformation matrix
 - ⇒ Approximation and possibility of error
- Device metamerism
 - Different surfaces under same illumination
 - » Same camera response ⇒ Same LMS value
- Solution
 - Spectral reflectance of most natural surfaces
 - » Smooth function of wavelength
 - » Representation by a small number of basis function

- Starling : **Surmising better color vision** than a human
 - Narrow action spectra
 - Evenly spaced across visible spectrum

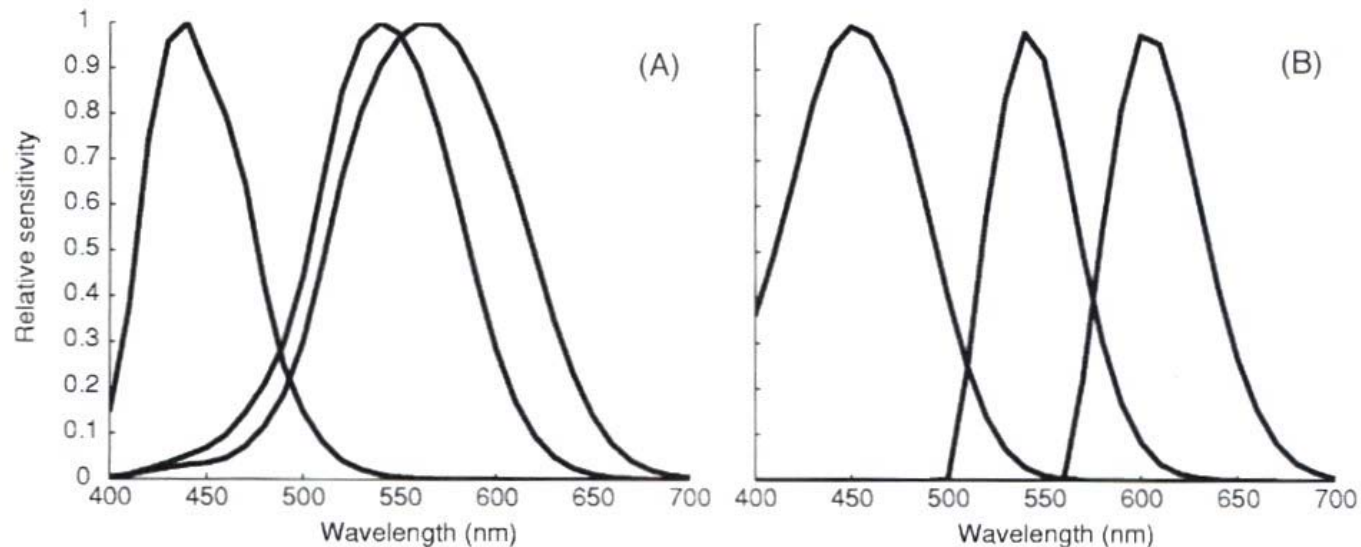


Fig. 2 (A) Cone sensitivities for human

(B) Cone sensitivities for starling

– Characterization of camera's RGB pixel value

- First stage

- Pointing the camera at Macbeth Color Checker card illuminated by a tungsten-halogen light source
- Illuminated a white card with same lamp
- Measurement of the CIE-Y value
- Allowed data (radiance) \Rightarrow camera output (RGB)
 - » Nonlinear relation
 - \Rightarrow Linearization

- Second stage
 - Measurement of camera sensor's **spectral sensitivities**
 - » By pointing camera at a white target
 - ⇒ approximately 99% reflectance
 - Image of target
 - » Set of 31 narrowband color filters(10nm), range 400-700nm
 - Measurement of **spectral radiance** through the same filters
 - Using second-order polynomial regression
 - » To map linearized RGB into LMS
 - This characterization
 - » Given a reflectance and illumination
 - ⇒ **Camera response value** and **LMS value**

– Computing LMS output

$$L = \sum_{\lambda} l(\lambda)^* Q(\lambda)^* I(\lambda) \quad (1)$$

$$M = \sum_{\lambda} m(\lambda)^* Q(\lambda)^* I(\lambda) \quad (2)$$

$$S = \sum_{\lambda} s(\lambda)^* Q(\lambda)^* I(\lambda) \quad (3)$$

Where l,m,s are cone sensitivities

λ is wavelength

Q is spectral reflectance

I is spectral radiance of the illuminant

– Computing camera's response

$$R = \sum_{\lambda} r(\lambda)^* Q(\lambda)^* I(\lambda) \quad (4)$$

$$G = \sum_{\lambda} g(\lambda)^* Q(\lambda)^* I(\lambda) \quad (5)$$

$$B = \sum_{\lambda} b(\lambda)^* Q(\lambda)^* I(\lambda) \quad (6)$$

Where r,g,b are camera's spectral sensitivities

- Mapping RGB to LMS using polynomial transform for other data
- Relative error of the polynomial transform

$$Err = \frac{\sqrt{(L - \hat{L})^2 + (M - \hat{M})^2 + (S - \hat{S})^2}}{\min(\sqrt{L^2 + M^2 + S^2}, \sqrt{\hat{L}^2 + \hat{M}^2 + \hat{S}^2})} \quad (7)$$

Where $\hat{L}, \hat{M}, \hat{S}$ represent the mapped cone activities

- Mean error (Err) for human
 - Northern European dataset : 0.034 (SD=0.034, n=1095)
 - Ugandan dataset : 0.016 (SD=0.0159, n=783)
- Mean error (Err) for starling
 - Northern European dataset : 0.056 (SD=0.05, n=783)
 - Ugandan dataset : 0.01 (SD=0.01, n=1095)

◆ Datasets

– First

- 113 image of fruit taken in Kibale Forest, Uganda

– Second

- Time-lapse sequence (4 min interval) taken from dawn to dusk in a British garden
- Measurement (1-2 min interval) of total **radiance** and of **spectrum** of patch gray card

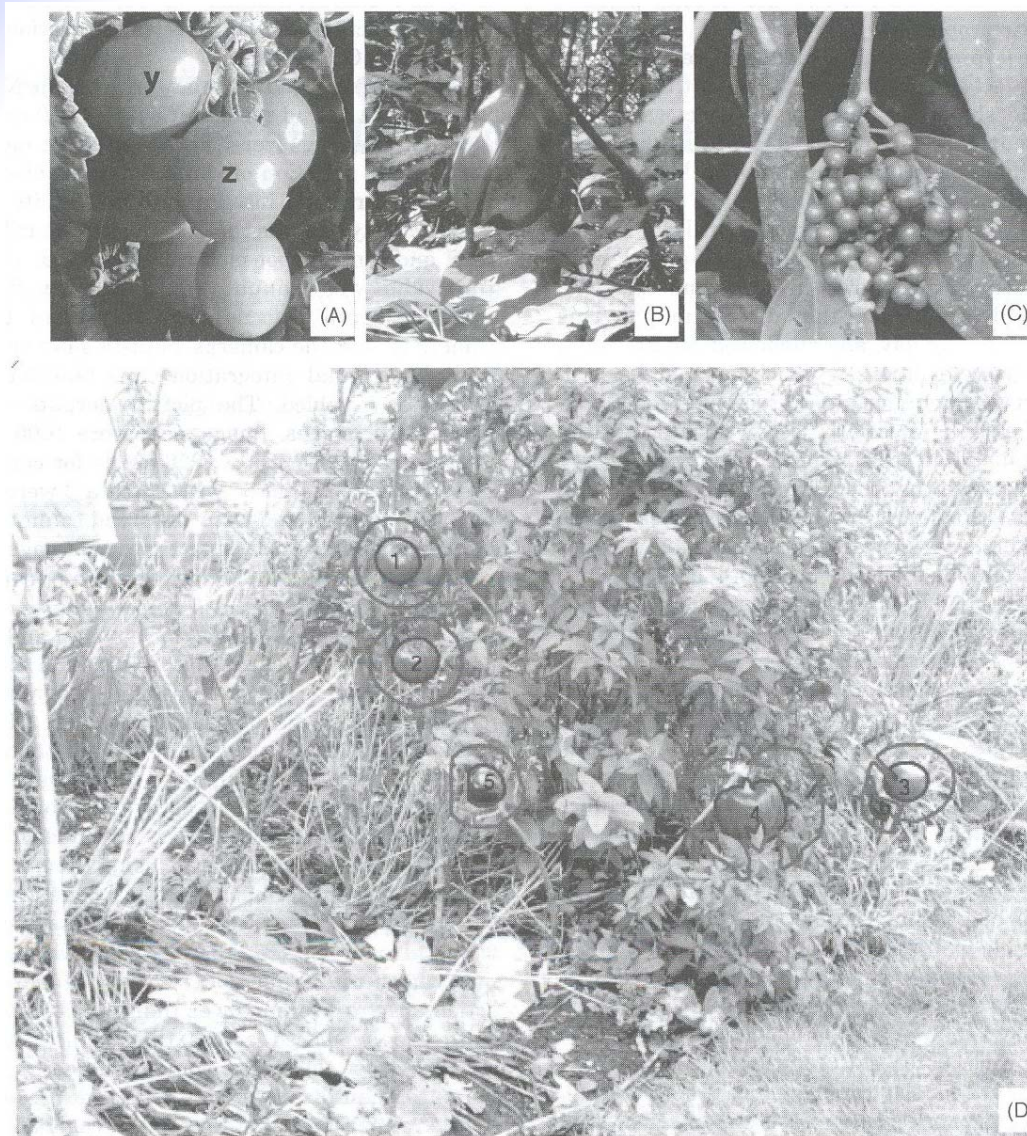


Fig. 1

- (A) Ripe and unripe tomatoes
x is shadowed
y and z are illuminated
- (B), (C) Photographs of ripe fruit
taken from the Kibale
- (D) One of time-lapse sequence
taken at 4 min intervals from
dawn till dusk

◆ Modeling and calculation of opponent signals

– Definition of calculation for Lum, RG, BY

$$Lum = L + M \quad (8)$$

$$RG = L / Lum \quad (9)$$

$$BY = S / Lum \quad (10)$$

$$RG = (L - M) / Lum \quad (9a)$$

– Noise

$$n = s^* \exp(y) \quad (11)$$

Where n is **noisy signal**

s is **L,M,S signal** estimated from our calibrated camera

y is **random variable** with a standard deviation matching the Weber fraction for L,M,S channels

◆ Distinguishing fruit from leaves

- Degree of Opponent signal : Helping separate a fruit from surrounding leaves

$$d' = \frac{\sqrt{2|\langle x \rangle - \langle y \rangle|}}{\sqrt{\sigma^2(x) + \sigma^2(y)}} \quad (12)$$

Where x values represent the activation level for the signal (fruit)

y values represent the activation level for the noise (leafy surround)

Results

- ◆ Examining opponent channel activation for directly illuminated and shadowed fruit
 - d' value : RG channel > BY channel
 - RG system
 - Contrast of red and green
 - Close position of the L and M cones
 - » Insensitive to variation in illumination
 - Substantial effect in BY system illuminated and shadowed area
 - Illuminated object : white or yellow
 - Shadowed object : blue

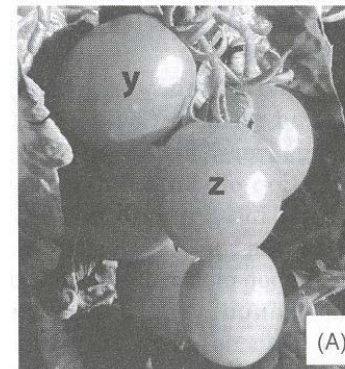
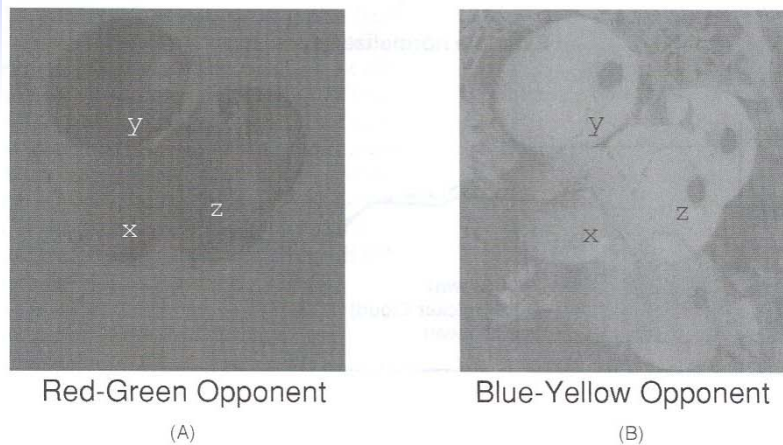


Fig. 1 (A) Photograph of tomatoes against background of leaves (some ripe, some not)

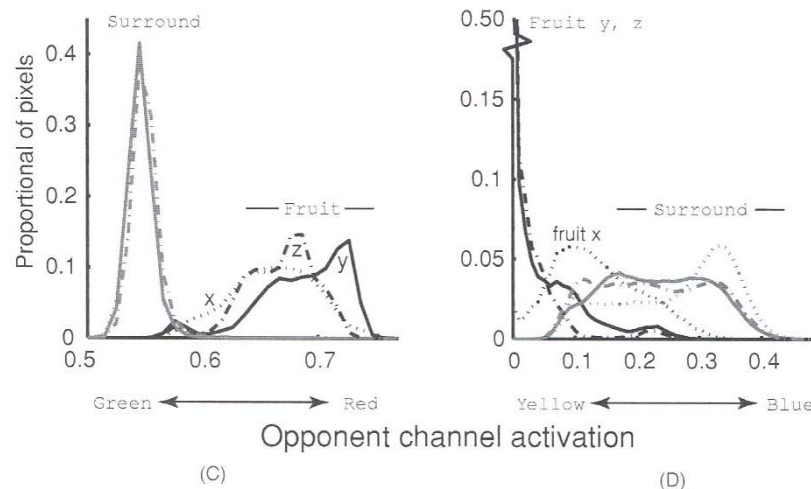
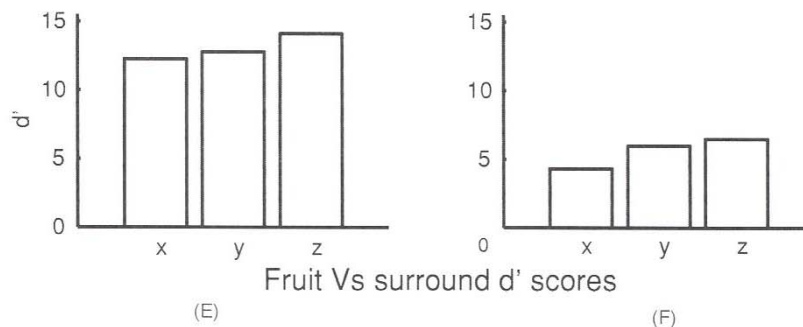


Fig. 3

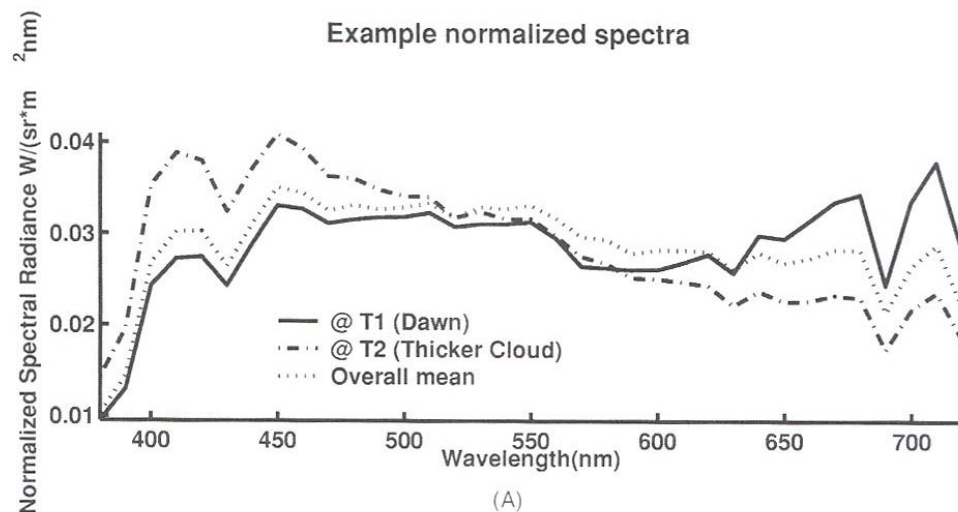
(A),(B) Gray level representation of the signals in the primate RG and BY opponent channels

(C),(D) Histogram of pixel activity level for the ripe fruit (x,y,z) and the area surrounding

(E),(F) d' value ripe fruit compared with surrounding



◆ Changes in the illuminant during a day



Illuminant from spectroradiometry represented in opponent channel space

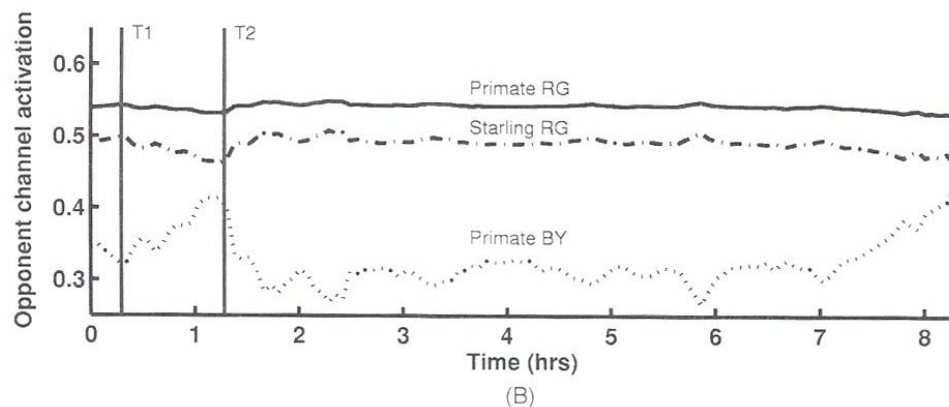


Fig. 4 Spectral radiance measure of sunlight

(A) Normalized spectra at T1 and T2

(B) Chromatic opponent signals of the light reflected

◆ Opponent encoding of fruit and foliage at different times of day

– Stability of the illuminant

- Stability of the illuminant in RG opponent system
- Instability of the illuminant in BY opponent system

– d' in each system

- d' in Lum channel : Primate < starling
- d' in RG channel : Primate > starling

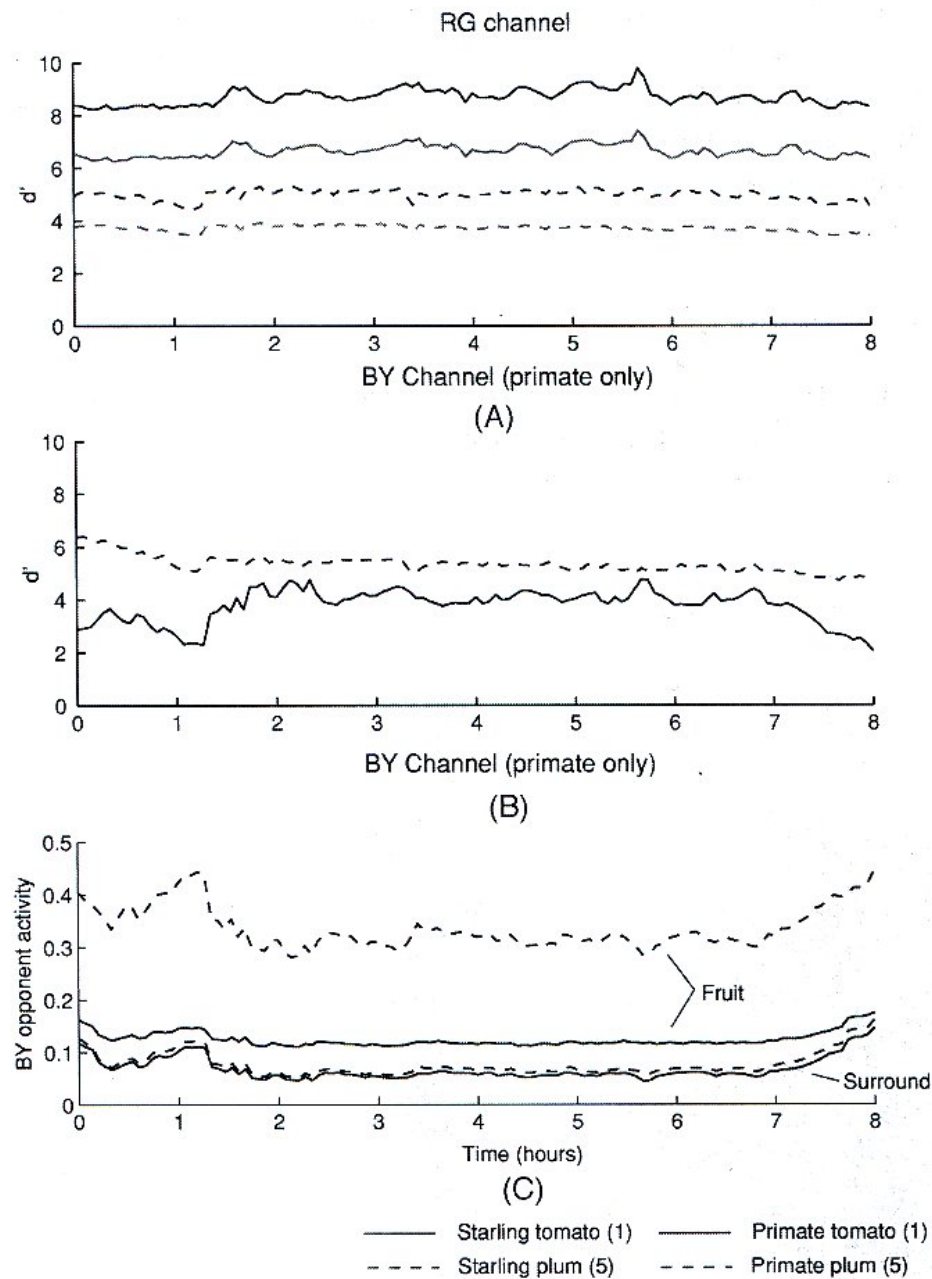


Fig. 5 (A) d' value for RG signal
 (B) d' value for BY signal
 (C) Actual BY signals generated from the plum, tomato, and leafy surrounds

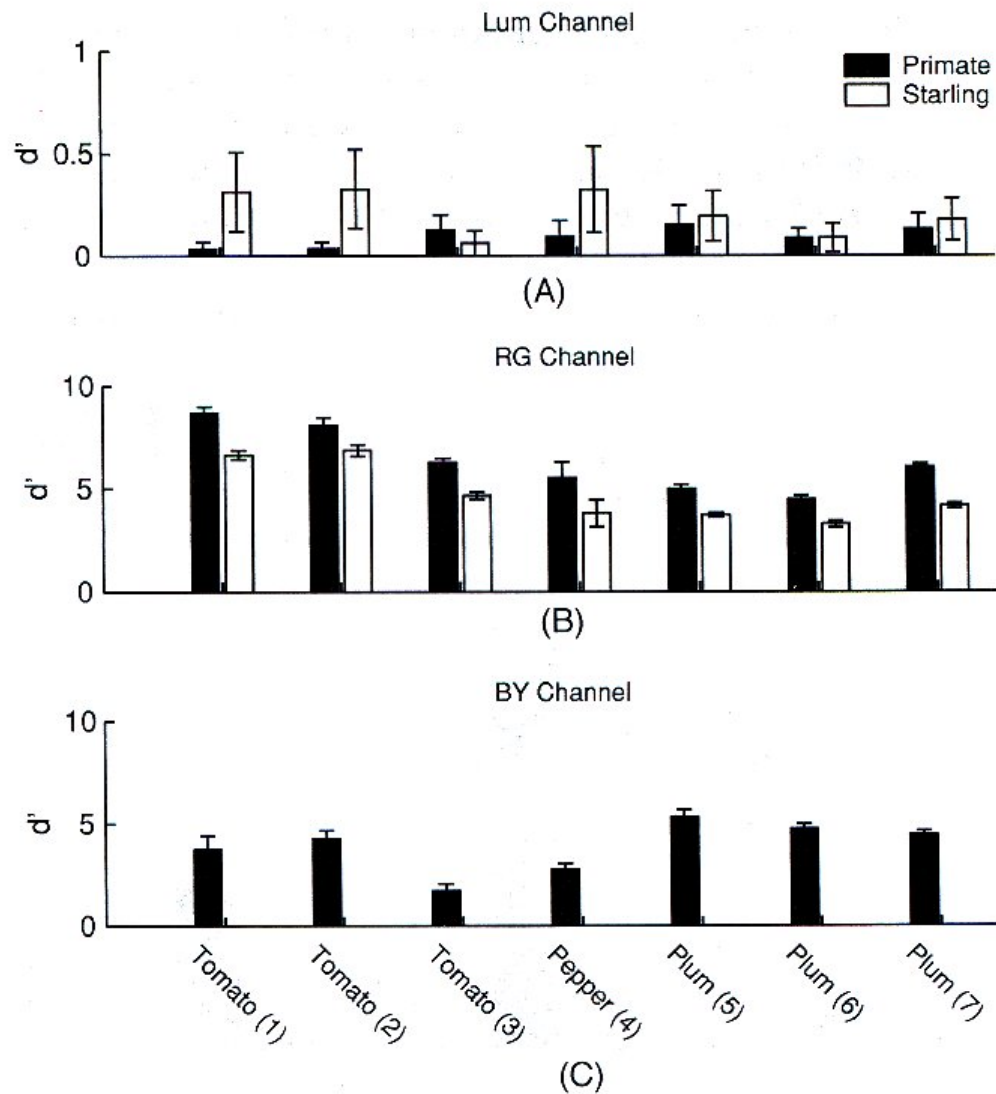


Fig. 6 (A) Mean d' score in the Lum channel
 (B) Mean d' score in the RG channel (C)
 Mean d' score in the BY channel

◆ Opponent encoding of fruit and foliage photographed in Kibale Forest

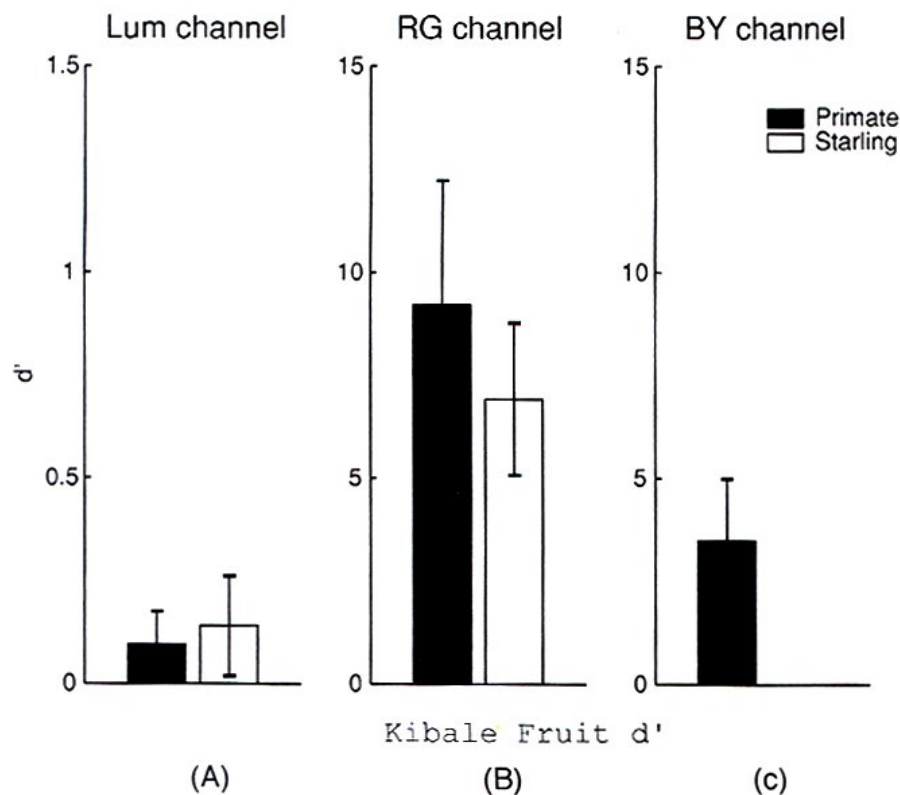


Fig. 7 Analysis of 113 photographs of fruit in Kibale Forest

d' value (A) luminance signal

(B) RG opponent signal

(C) BY opponent signal

- ◆ What factors led to the discrepancy in the d' scores for the primate and starling RG channel?
 - Difference in starling and primate L and M cones
 - Closely spaced primate cone
 - Different bandwidth of the action spectra of the cone (human : 40nm, starling : 20nm)

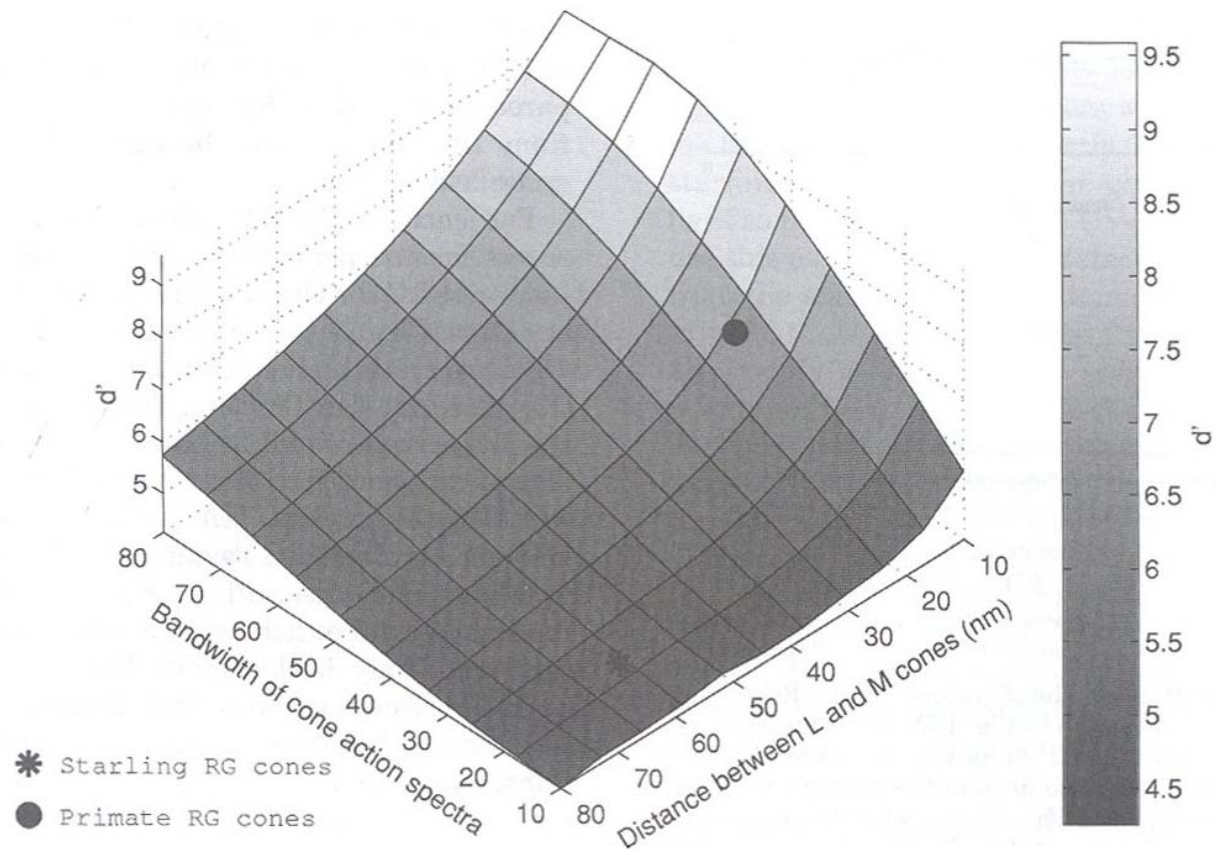


Fig. 8 Reanalysis of time-lapse photograph in Fig. 3.
Varying the position of L cone and the bandwidth of the L and M cones.

Discussion

- ◆ Advantage of BY system
 - Having large output
 - Good operation at low signal-to-noise (low luminance level)
 - Good segmentation of the scene into areas of different spectral reflectance
- ◆ Two important properties of RG system in primate
 - Optimal setting to distinguish edible fruit from leaves
 - Ignorance shadow and changes in illumination

◆ Creature with RG system : Bird

- Inference of better color vision in bird than human
 - Narrow bandwidth
 - Evenly spaced across visible spectrum
- Having not always in advantage
 - Larger possibility of confusion by shadows and changes of illuminance

◆ Provision of indications about the functional role of the peculiar color vision system