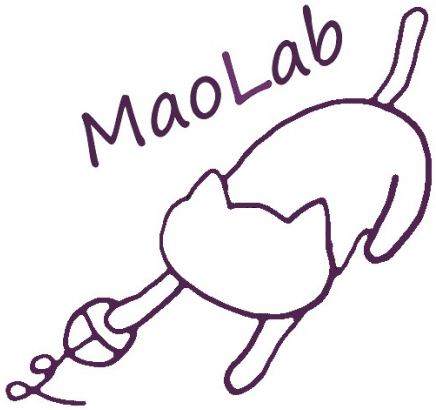
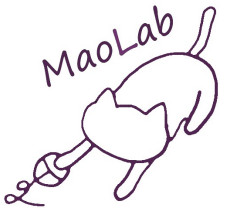
Processing images for red–green dichromats compensation via naturalness- and information-preservation considered recoloring

Z. Zhu[1], M. Toyoura[1], K. Go[1], I. Fujishiro[2], K. Kashiwagi[1], X. Mao[1]

1) University of Yamanashi
2) Keio University



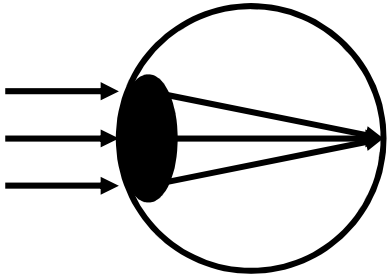
Color Vision Deficiency



Also known as

- **color blind** (monochromacy, dichromacy)
- **color weak** (anomalous trichromacy)

Normal

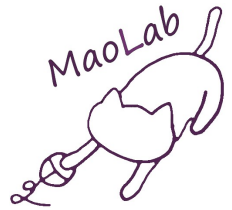


Red-Green Dichromacy

Purpose

propose a **recoloring algorithm** for red–green dichromacy compensation

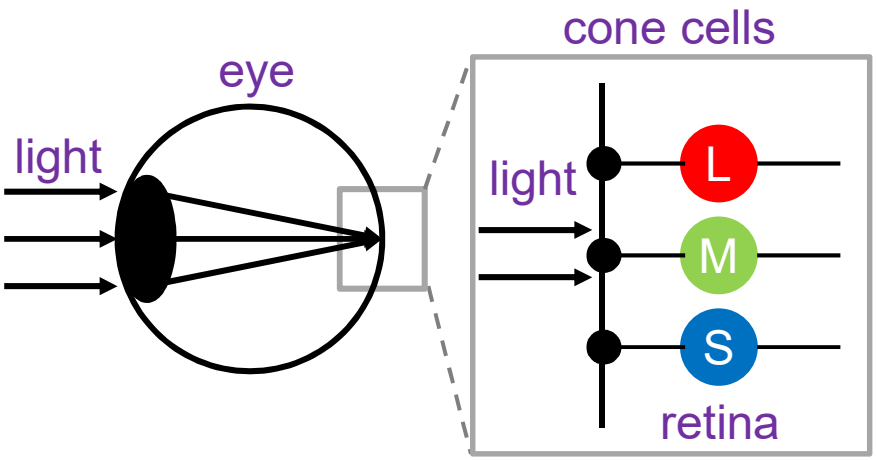
Contents



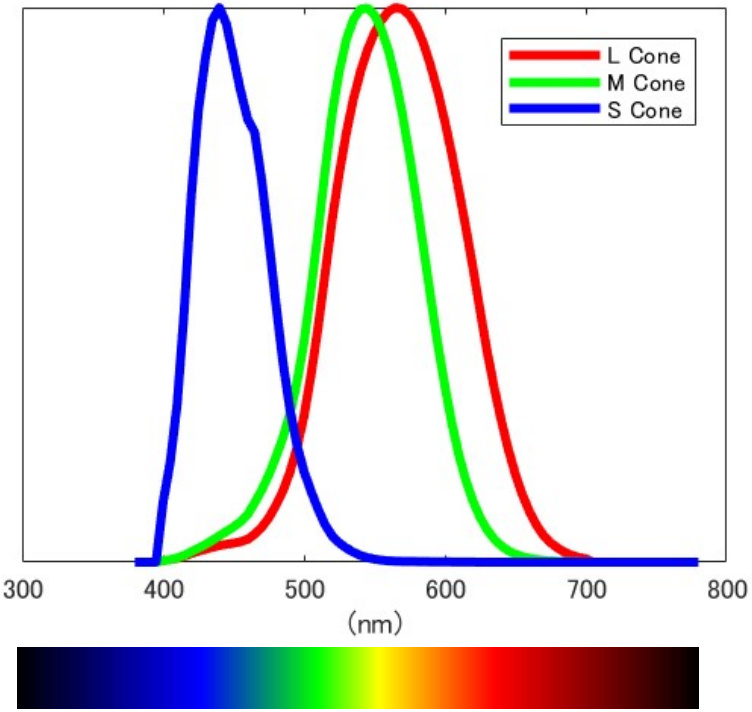
Color Vision Deficiency

Cone Cells: light stimulus → color vision

Normal color vision



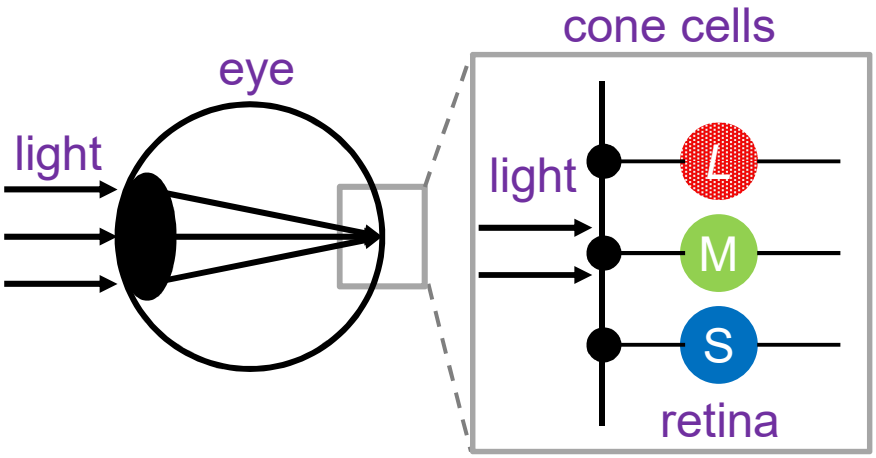
Responsivity spectra

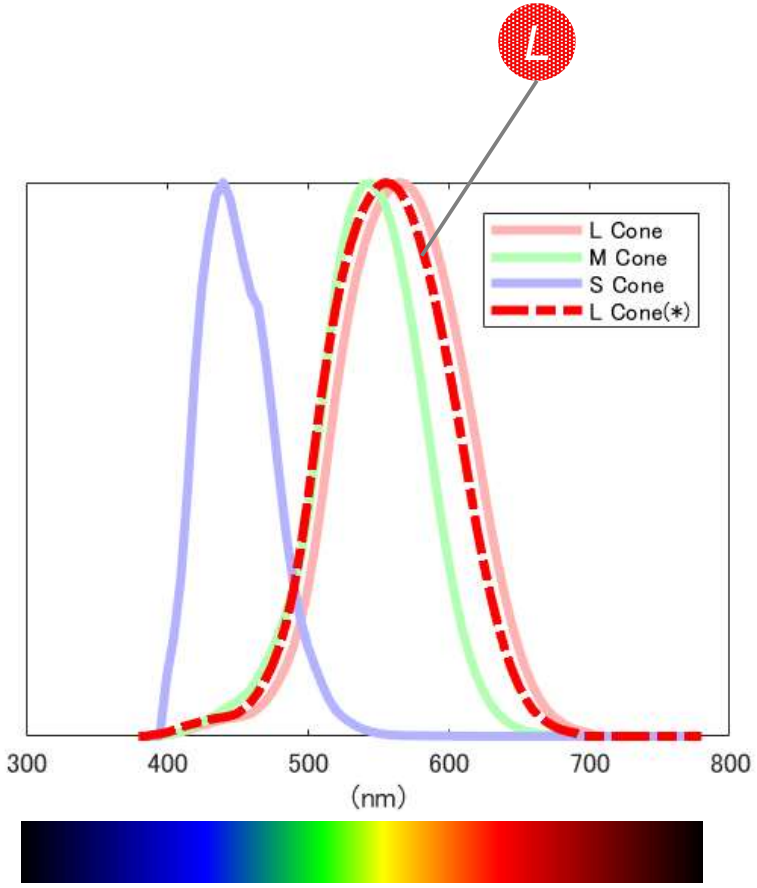


Color Vision Deficiency

Anomaly in cone cells: CVD

Anomaly in L cone

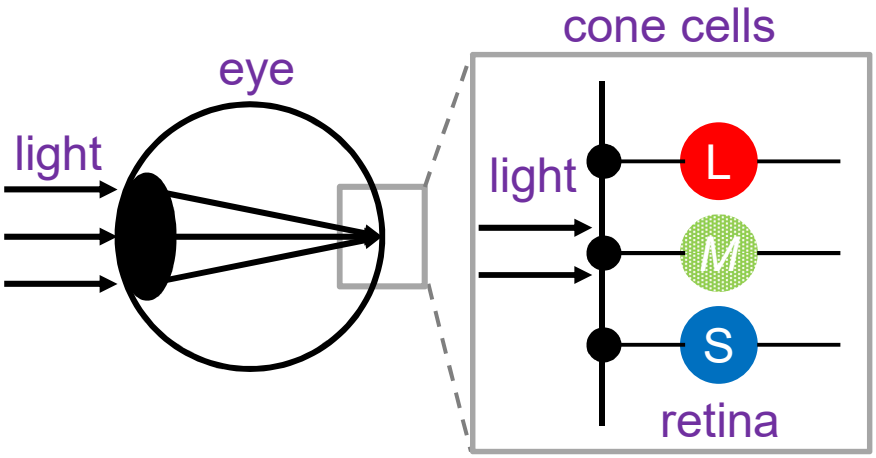


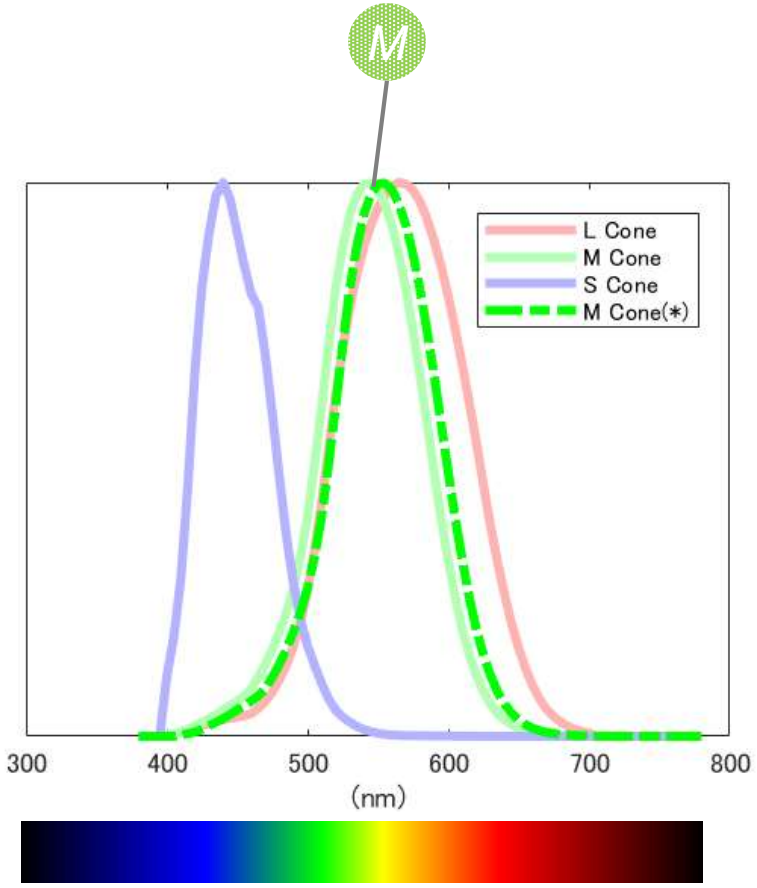


Color Vision Deficiency

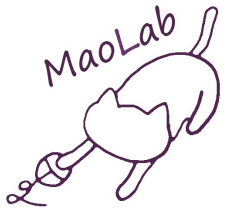
Anomaly in cone cells: CVD

Anomaly in M cone





Color Vision Deficiency



Most of CVDs are

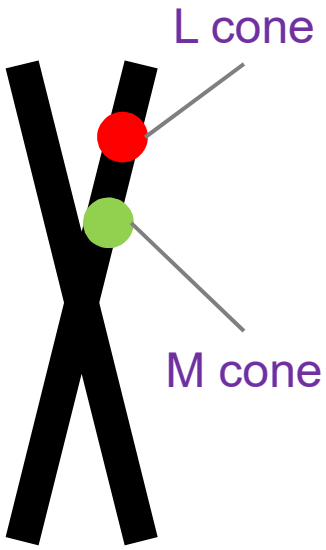
- red–green CVD (anomaly in L or M cone)

Incidence of red–green CVD

- X-chromosome heritability
- 5–8% for male, 0.8% for female

Red–Green Dichromacy further divided into

- **protanopia** (anomaly in L cone)
- **deuteranopia** (anomaly in M cone)

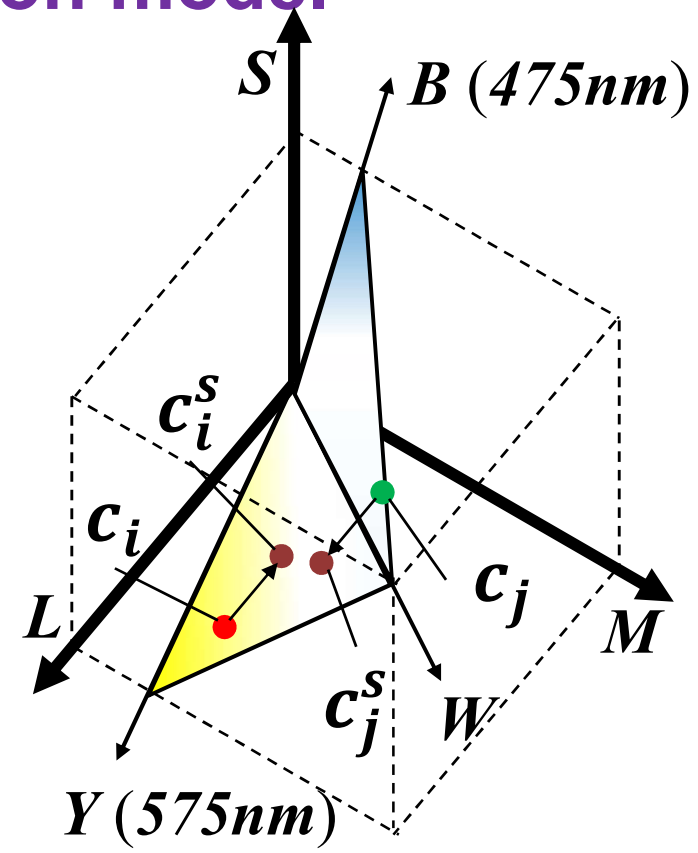


X-chromosome

Color Vision Deficiency

Brettel's dichromacy simulation model

- LMS color space
- color gamut of dichromacy:
  two half-planes
- projecting color to the half-plane
  along **abnormal axis**



Protanopia Simulation

Brettel, H., Viénot, F., & Mollon, J. D. (1997). Computerized simulation of color appearance for dichromats. *JOSA A*, 14(10), 2647-2655.

Color Vision Deficiency

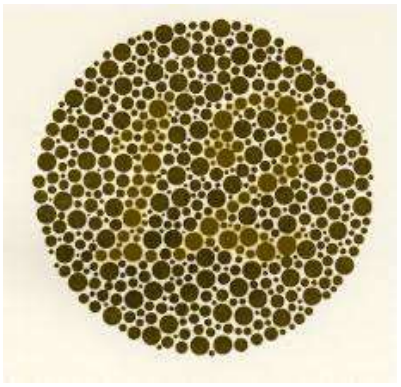
Simulation results of protanopia/deuteranpia (Brettel 1997)

Normal Individual

Normal Individual

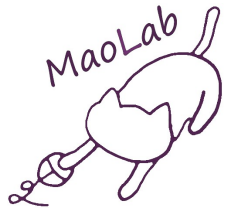
Contrast Loss

Protanope



Deuteranope

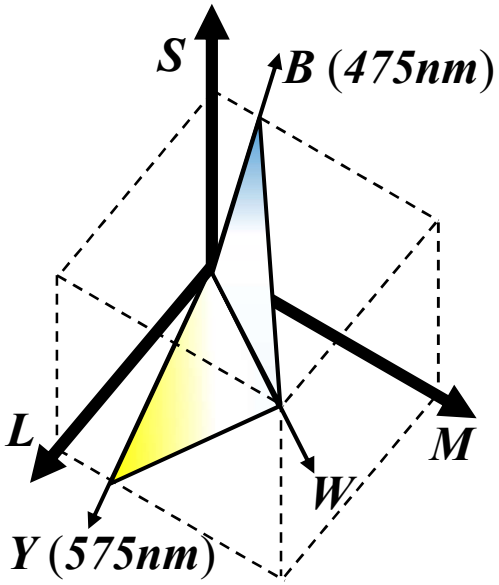
Existing Research

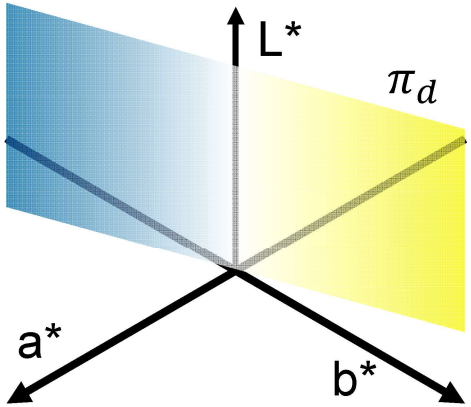


Machado et al. 2010

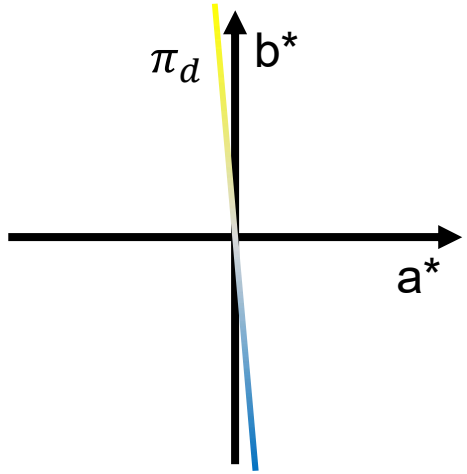
Maximizing global contrast

Color gamut of dichromacy in CIE L*a*b* color space (Lab): π_d





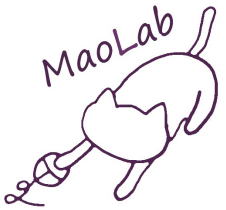
Color Gamut in Lab Space



View along L* axis

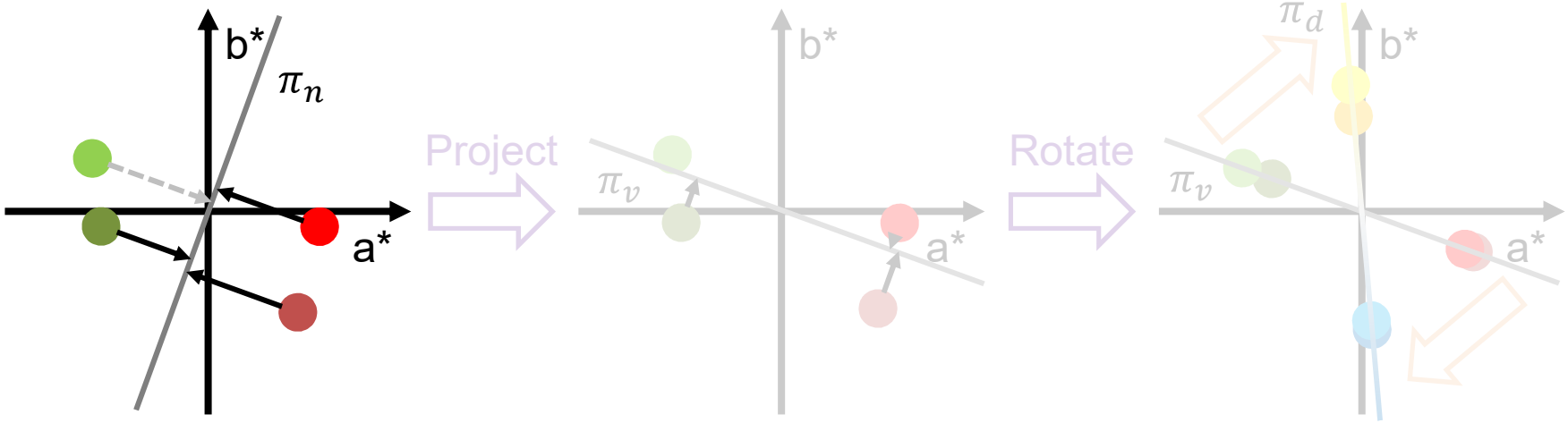
Machado, G. M., & Oliveira, M. M. (2010, June). Real - Time Temporal - Coherent Color Contrast Enhancement for Dichromats. In *Computer Graphics Forum* (Vol. 29, No. 3, pp. 933-942). Oxford, UK: Blackwell Publishing Ltd.

Existing Research



Machado et al. 2010

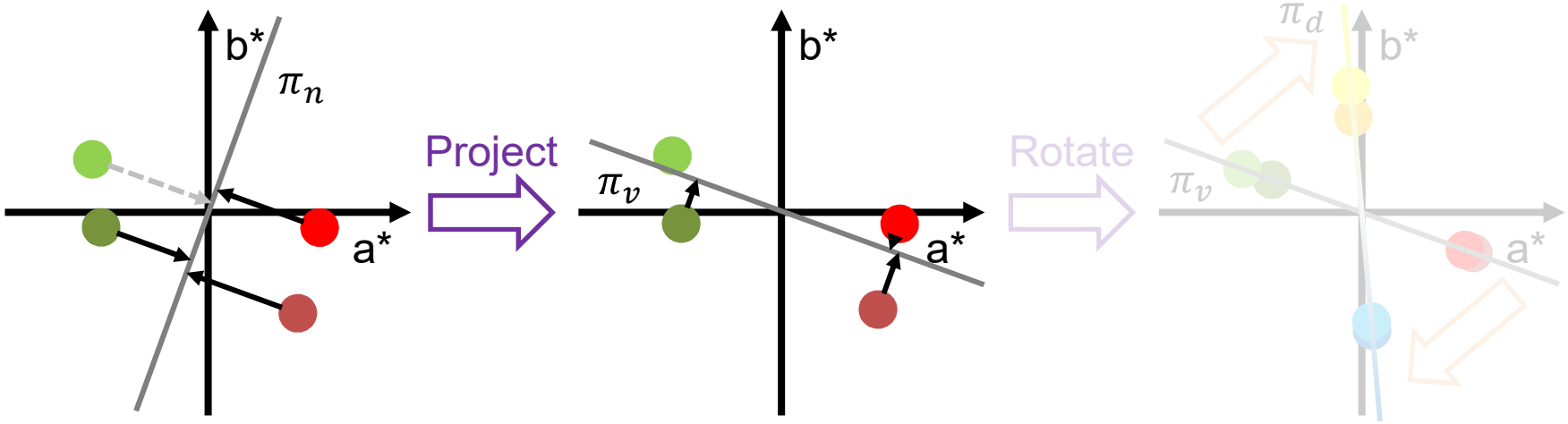
- obtain plane π_n which ***maximizes contrast loss*** in least-squares sense
- project all colors onto plane π_v which is orthogonal to π_n
- rotate π_v to align them to the plane of dichromacy π_d



Existing Research

Machado et al. 2010

- obtain plane π_n which maximizes contrast loss in least-squares sense
- project all colors onto plane π_v which is *orthogonal to* π_n
- rotate π_v to align them to the plane of dichromacy π_d



Existing Research

Machado et al. 2010

- obtain plane π_n which maximizes contrast loss in least-squares sense
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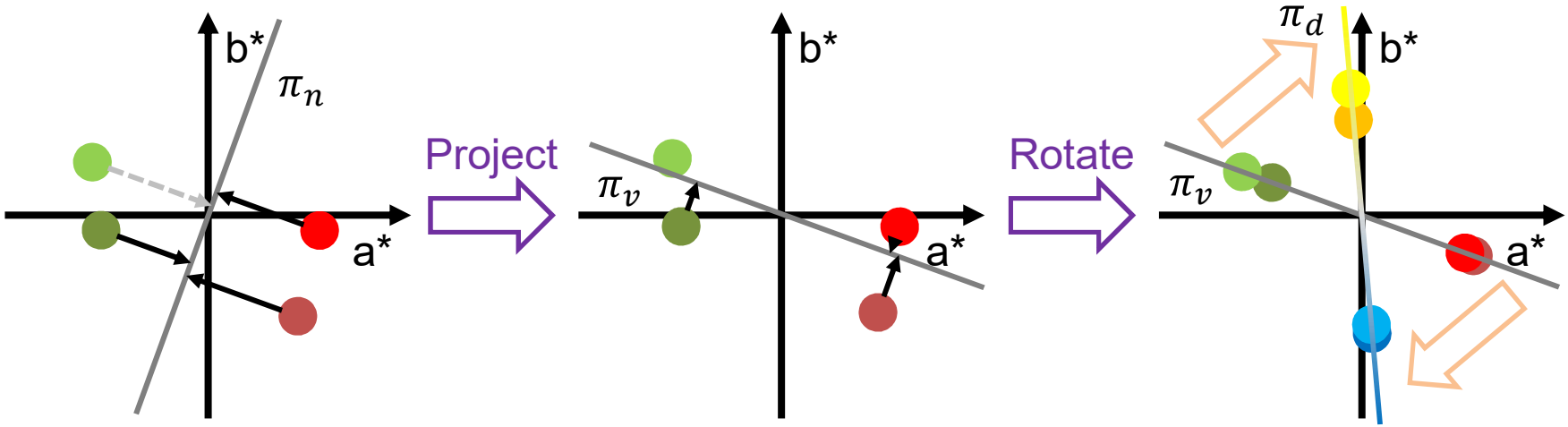


Existing Research

Result of Machado et al. 2010

- Cannot preserve colors which CVD can identify (blue, yellow)

Input

Machado et al. 2010

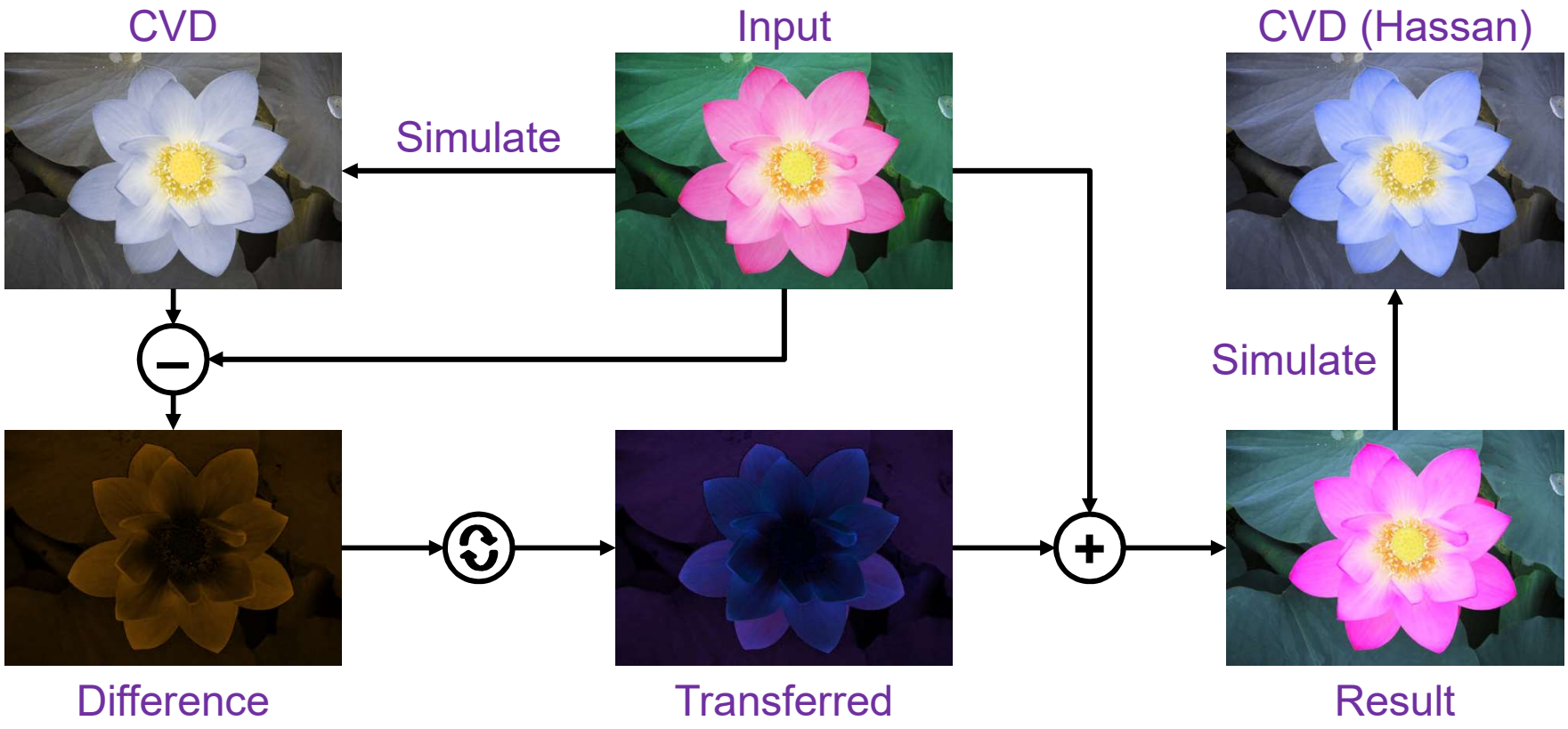
CVD

CVD (Machado)

Existing Research

Hassan et al. 2019

Increasing blue component of "problematic" colors



M.F. Hassan, Flexible color contrast enhancement method for red-green deficiency, Multidimensional Systems and Signal Processing (2019).

Existing Research

Result of Hassan et al. 2019

- contrast loss (difference between sun & sky)

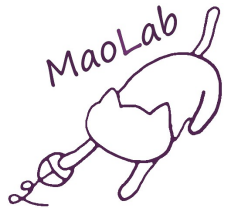
Input

Hassan et al. 2019

CVD

CVD (Hassan)

Proposed Method



We takes

- **contrast enhancement**
- **naturalness preservation**

into account

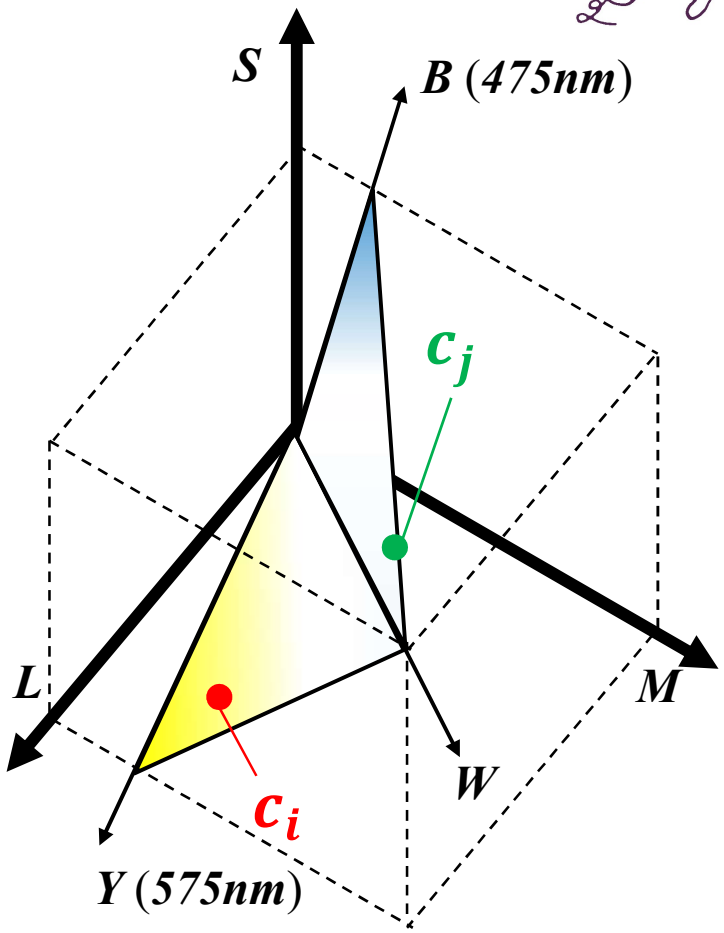
Naturalness

The image of the world for CVD

- deviation from the original perceived image should be minimized

Proposed Method

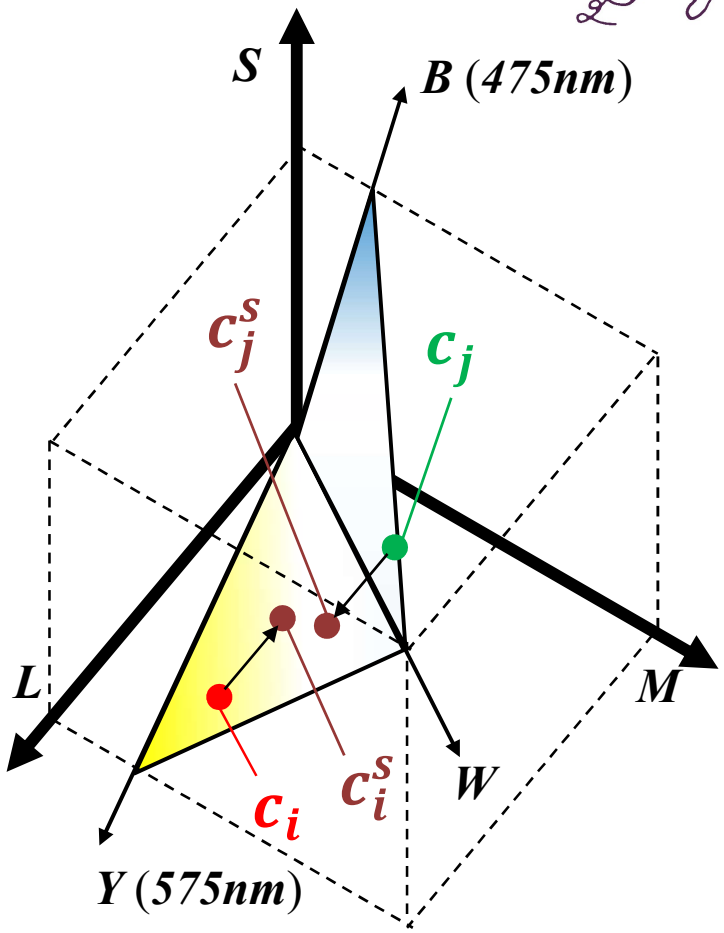
c_i, c_j: original colors



Proposed Method

c_i, c_j: original colors

c_i^s, c_j^s: CVD simulation of c_i, c_j

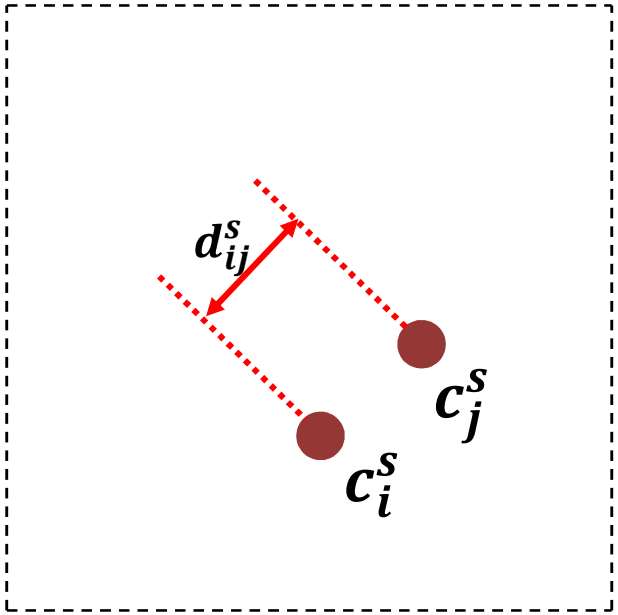


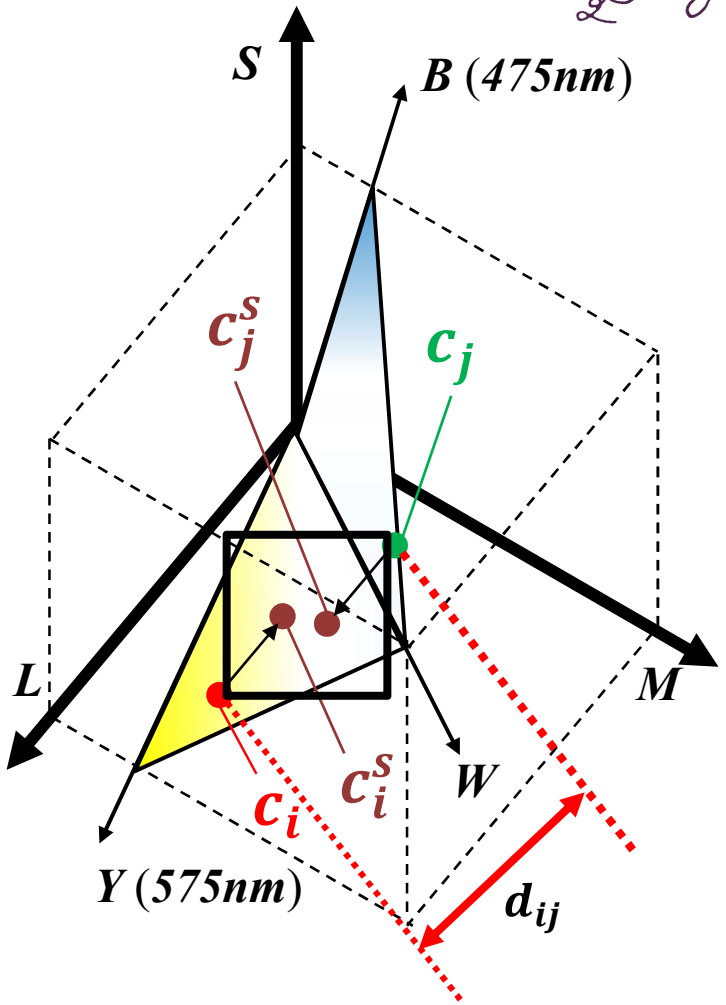
Protanopia simulation (projection along *L* axis)

Proposed Method

c_i, c_j: original colors

c_i^s, c_j^s: CVD simulation of c_i, c_j



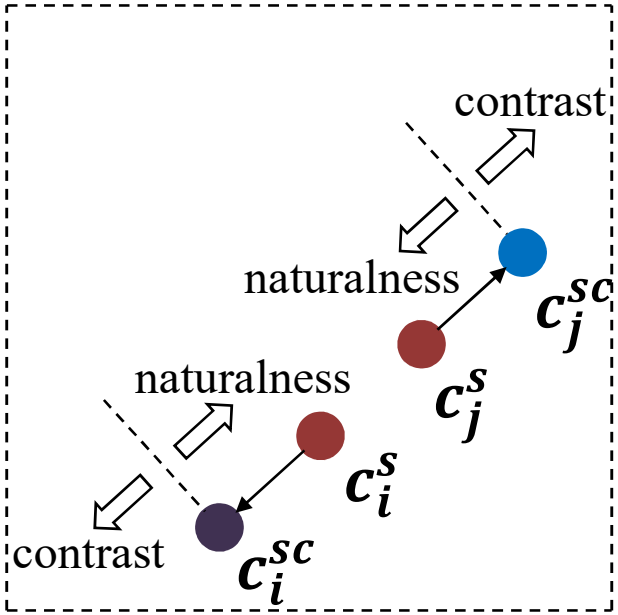


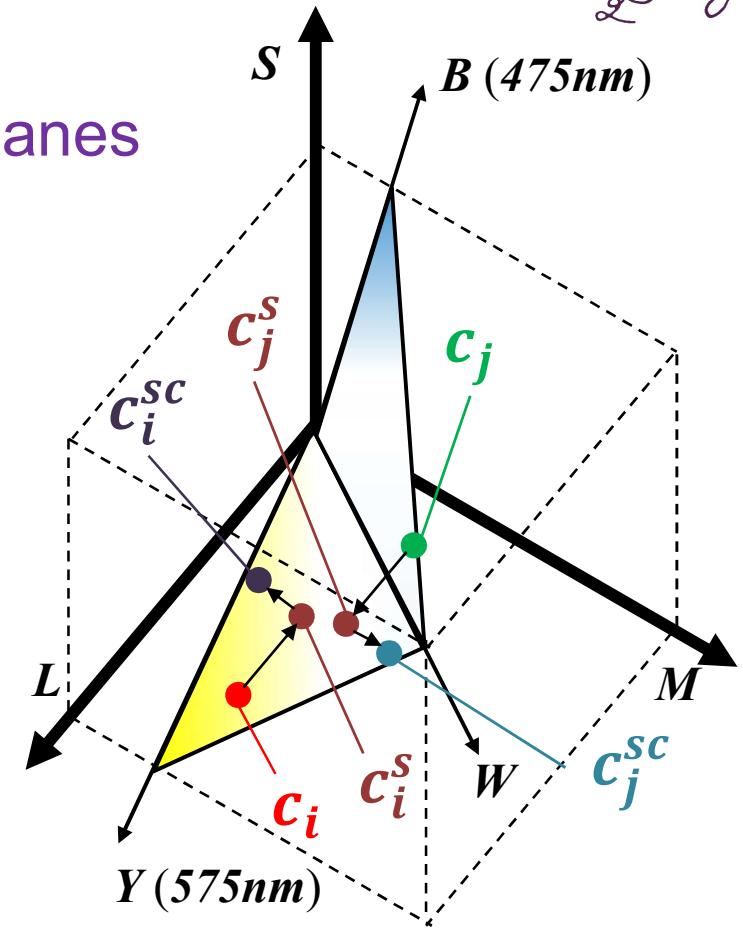
$d_{ij}^s \ll d_{ij}$→**contrast loss**

Proposed Method

c_i^{sc}, c_j^{sc}: optimized colors on half planes

δ_{ij}: contrast between colors c_i, c_j





$$\arg\min_{c_i'}\left(\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\underbrace{\left(c_i^{sc}-c_j^{sc}-\delta_{ij}\right)^2}_{\textbf{contrast}}+\lambda\sum_{i=1}^{N}\underbrace{(c_i^{sc}-c_i^{s})^2}_{\textbf{nature}}\right)$$

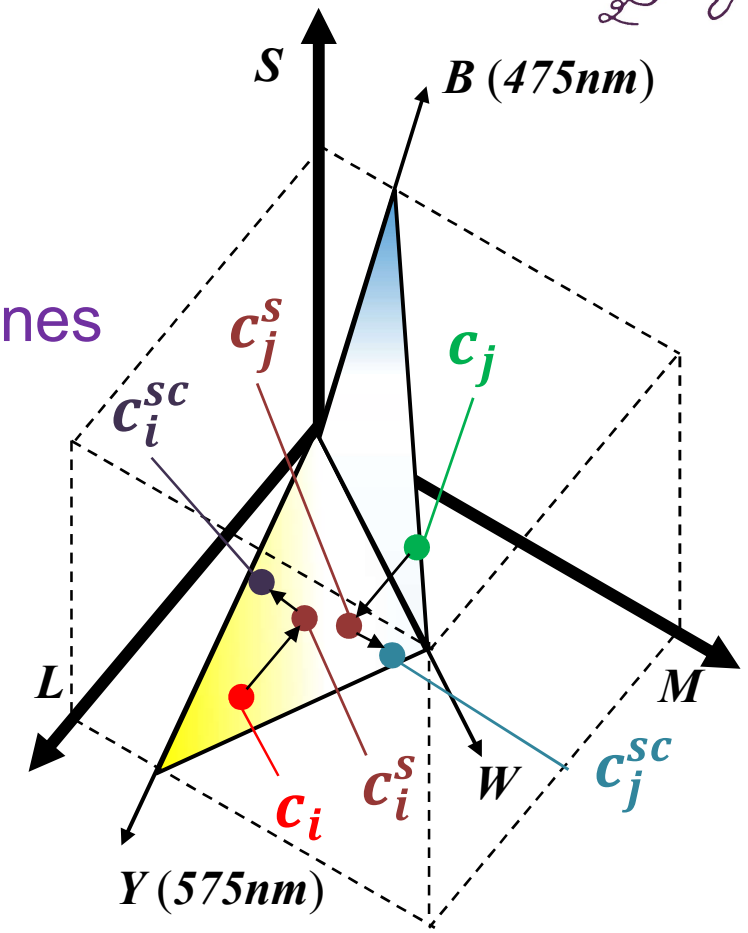
Proposed Method

c_i, c_j: original colors

c_i^s, c_j^s: CVD simulation of c_i, c_j

c_i^{sc}, c_j^{sc}: optimized colors on half planes

δ_{ij}: contrast between colors c_i, c_j



$$\arg\min_{c_i'}\left(\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\underbrace{\left(c_i^{sc}-c_j^{sc}-\delta_{ij}\right)^2}_{\textbf{contrast}}+\lambda\sum_{i=1}^{N}\underbrace{(c_i^{sc}-c_i^{s})^2}_{\textbf{nature}}\right)$$

Proposed Method

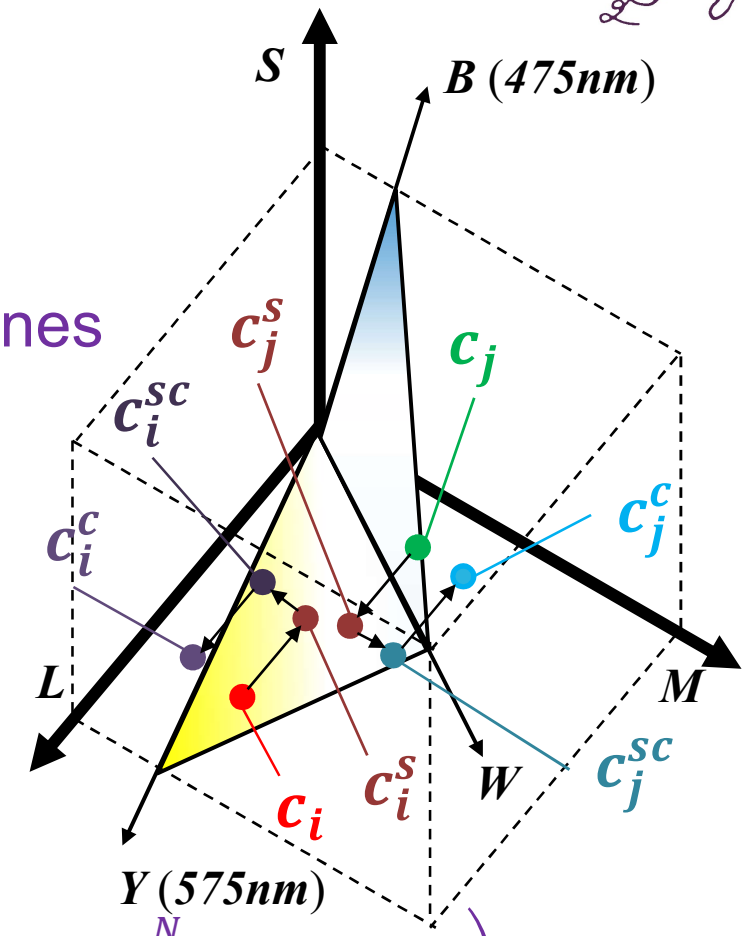
c_i, c_j: original colors

c_i^s, c_j^s: CVD simulation of c_i, c_j

c_i^{sc}, c_j^{sc}: optimized colors on half planes

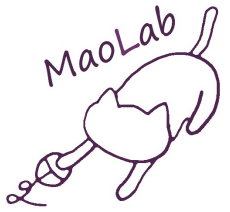
δ_{ij}: contrast between colors c_i, c_j

c_i^c, c_j^c: resulting colors in 3D space



$$\arg\min_{c_i'}\left(\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\underbrace{\left(c_i^{sc}-c_j^{sc}-\delta_{ij}\right)^2}_{\textbf{contrast}}+\lambda\sum_{i=1}^{N}\underbrace{(c_i^{sc}-c_i^s)^2}_{\textbf{nature}}\right)$$

Proposed Method



Proposed model

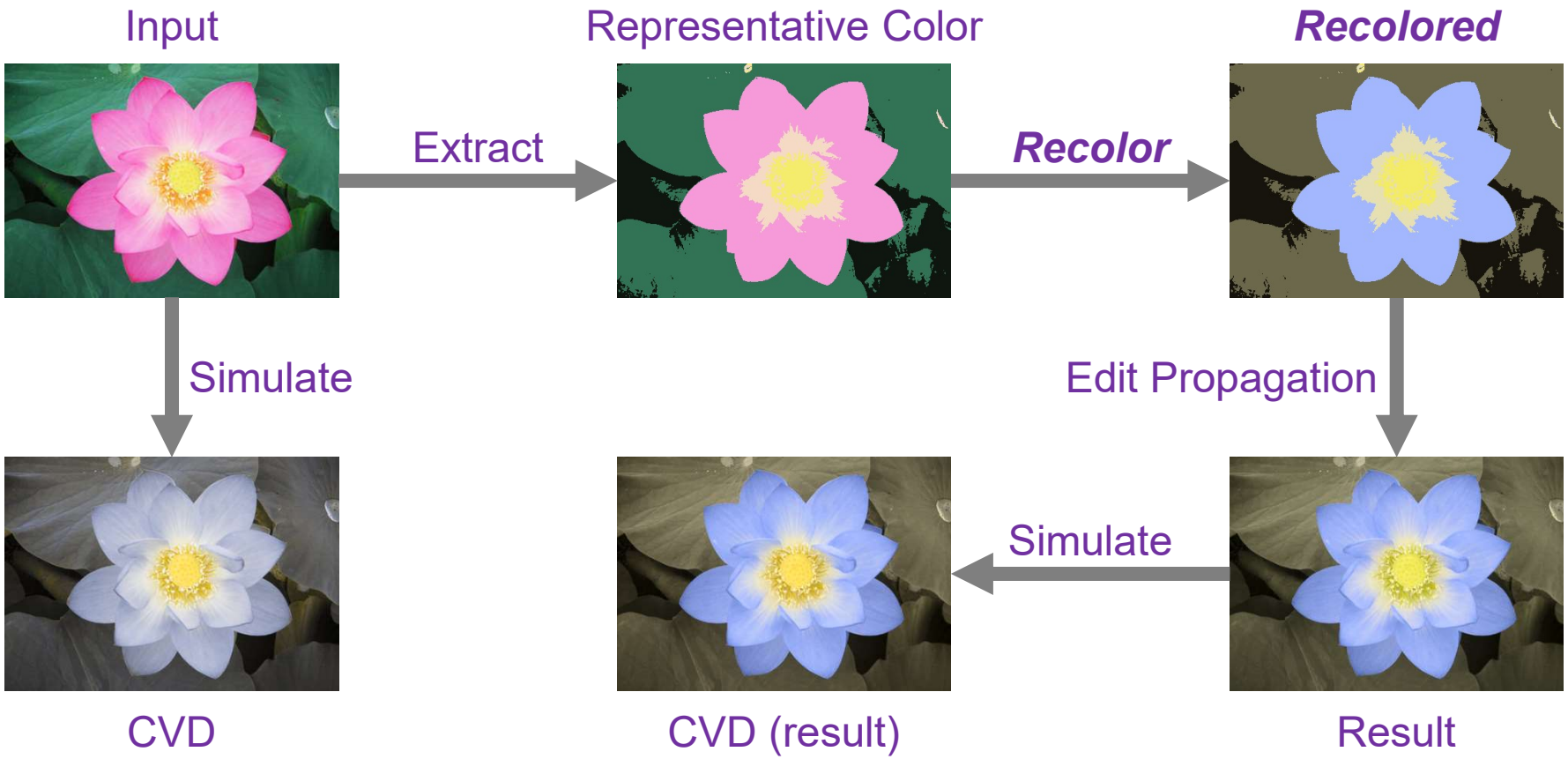
$$\arg\min_{c_i'}\left(\sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N}\underbrace{\left(c_i^{sc}-c_j^{sc}-\delta_{ij}\right)^2}_{\textbf{contrast}}+\lambda\sum_{i=1}^{N}\underbrace{(c_i^{sc}-c_i^{s})^2}_{\textbf{naturalness}}\right)$$

Partial derivative

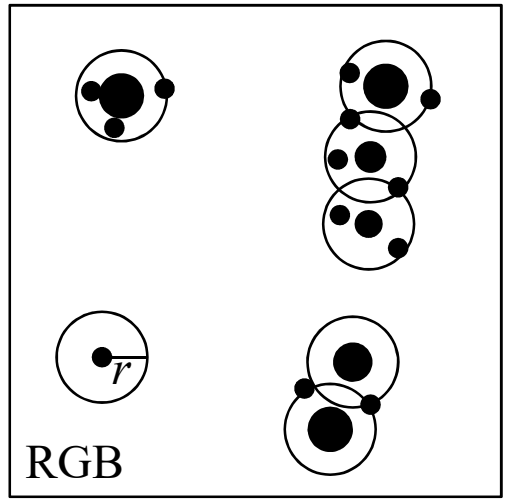
$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{bmatrix}$$

- $Ax = b$: A is ***non-sparse*** matrix, memory occupying

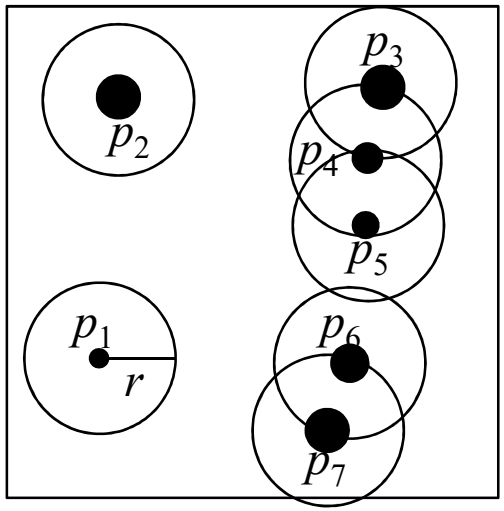
Implementation



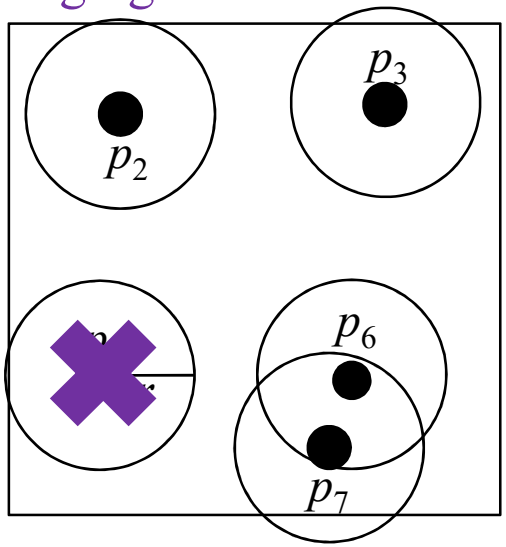
Representative Color Extraction



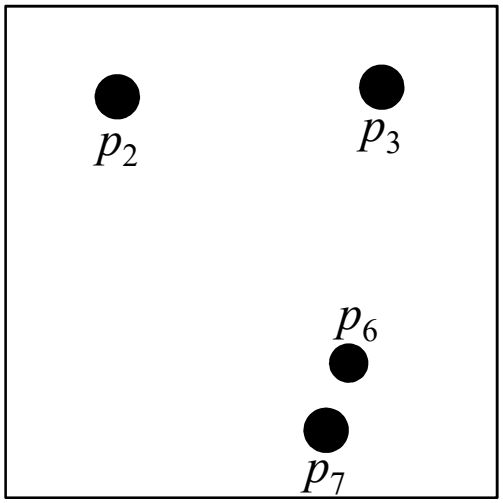
Cluster Extraction



Cluster Merging



Noise Rejection



Result

Input

Machado

Hassan

Proposed

CVD

CVD (Machado)

CVD (Hassan)

CVD (Proposed)

Result

Input

Machado

Hassan

Proposed

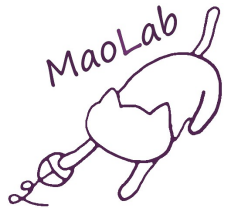
CVD

CVD (Machado)

CVD (Hassan)

CVD (Proposed)

Evaluation



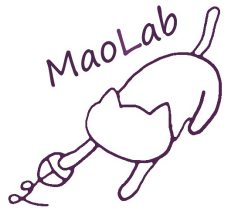
Evaluate the proposed method in terms of

- contrast enhancement
- naturalness preserving

Methods

- quantitative evaluation
- subjective experiment

Quantitative Evaluation



Absolute contrast metric: average gradient norm (AGN)

$$\mathbf{AGN} = \frac{1}{N}\sum_{i=1}^{N}\left(\sqrt{G_h(i)^2 + G_v(i)^2}\right)$$

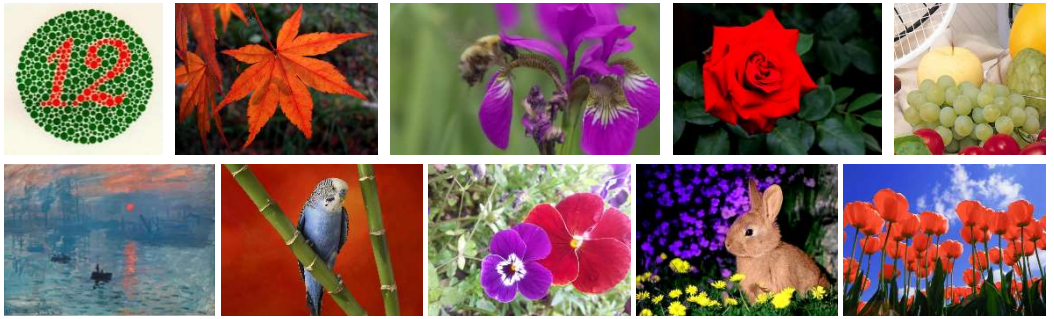
$G_h(i)$, $G_v(i)$: horizontal, vertical Sobel gradient operators

Gibson, K. B., & Nguyen, T. Q. (2013). A no-reference perceptual based contrast enhancement metric for ocean scenes in fog. IEEE Transactions on Image Processing, 22(10), 3982-3993.

Quantitative Evaluation

10 images consist of

- natural scenes
- artificial objects

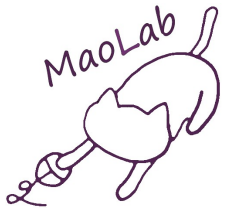


selected from color-to-gray benchmark

Average AGN Scores of 10 images

CVD Type	CVD	Machado	Hassan	Proposed
Protan	0.251	0.241	0.250	**0.256**
Deutan	0.258	0.254	0.257	**0.273**

Quantitative Evaluation



Naturalness: chromatic difference between c_i^{sc} and c_i^s

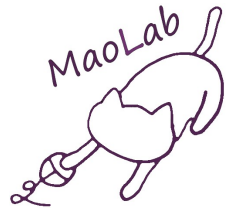
$$\mathbf{ACD} = \frac{1}{N}\sum_{i=1}^{N}\left(\sqrt{CD_a(i)^2 + CD_b(i)^2}\right)$$

$CD_a(i)$, $CD_b(i)$: a*, b* component difference between c_i^{sc}, c_i^s

Average ACD Scores of 10 images

CVD Type	Machado	Hassan	Proposed
Protan	16.0	11.0	**10.2**
Deutan	16.8	**8.3**	11.7

Subjective Evaluation

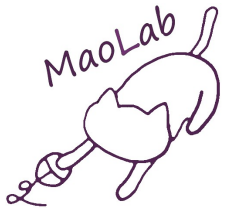


Subjects

- protan: severe 2, mild 3
- deutan: severe 3, mild 4

Recruited on campus by posting posters

Subjective Evaluation



Naturalness evaluation

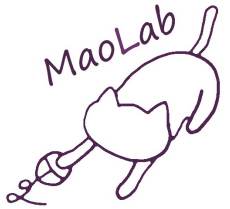
Tasks:

subjects are asked to label image

1. either “unnatural” or “natural”
2. naturalness order from 1 to 4

10 images same as those used in quantitative evaluation

Subjective Evaluation



Naturalness evaluation

Stimulus:

Input image and all recolored images are presented in a ***random*** order

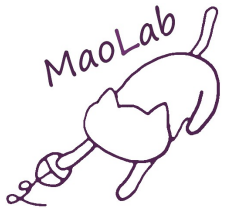
①

③

4

②

Subjective Evaluation



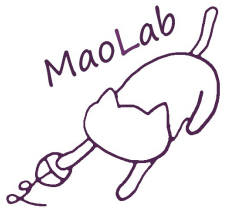
Average number of times the three methods received the "natural" label from subjects with severe CVD

CVD Type	Input	Machado	Hassan	Proposed
Protan	0.75	0.25	0.35	**0.65**
Deutan	0.80	0.37	0.57	**0.60**

Average number of times the three methods received the "natural" label from subjects with mild CVD

CVD Type	Input	Machado	Hassan	Proposed
Protan	0.90	0.23	**0.60**	0.53
Deutan	0.93	0.38	**0.63**	0.48

Subjective Evaluation



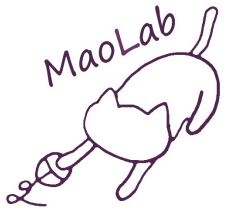
Average naturalness rank of the three methods sorted by subjects with severe CVD

CVD Type	Input	Machado	Hassan	Proposed
Protan	1.75	3.00	3.05	**2.20**
Deutan	1.90	3.13	2.67	**2.30**

Average naturalness rank of the three methods sorted by subjects with mild CVD

CVD Type	Input	Machado	Hassan	Proposed
Protan	1.73	3.27	**2.40**	2.60
Deutan	1.50	3.20	**2.43**	2.88

Subjective Evaluation



Contrast enhancement evaluation

Task:

Subjects are asked to label images as

- information decreased (-1)

  e.g. texture on flower petal disappeared

- information unchanged (0)

  e.g. almost no change from the input image

- information increased (+1)

  e.g. texture on flower petal becomes visible, contrast is enhanced

10 images used in quantitative evaluation

Subjective Evaluation

Contrast enhancement evaluation

Stimulus:

The positions of recolored images are randomly decided

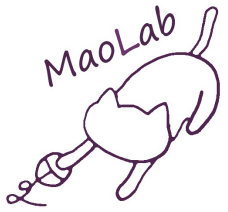
Input Image

-1

+1

+1

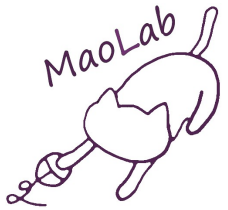
Subjective Evaluation



The average number of times the three methods received each label from subjects with **severe** CVD

CVD Type	Label	Machado	Hassan	Proposed
Protan	Increased	0.25	0.10	**0.35**
	Decreased	0.60	0.40	**0.25**
Deutan	Increased	0.07	0.03	**0.10**
	Decreased	0.83	0.77	**0.40**

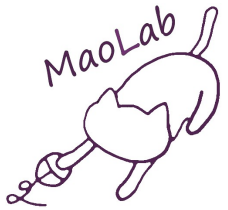
Subjective Evaluation



The average number of times the three methods received each label from subjects with **mild** CVD

CVD Type	Label	Machado	Hassan	Proposed
Protan	Increased	0.17	0.17	**0.30**
	Decreased	0.50	**0.40**	0.43
Deutan	Increased	**0.23**	0.10	**0.23**
	Decreased	0.60	0.33	**0.25**

Summary



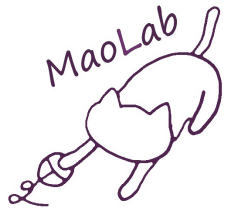
Proposed method achieved two goals simultaneously

- contrast enhancing
- naturalness preserving

Future work

- mild CVD compensation (80% of CVD)
- accelerate the algorithm

Acknowledgements



Thanks to all the volunteers who helped with the evaluation

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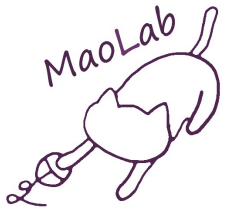

Thank you for your attention

Q & A