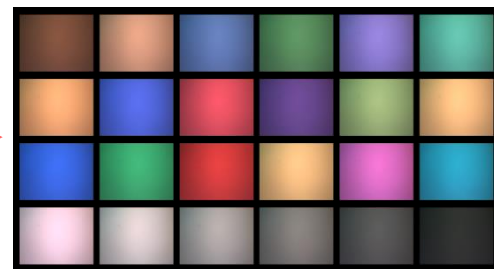
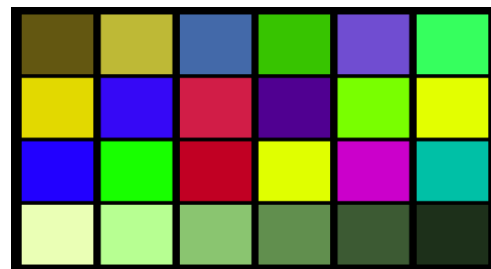
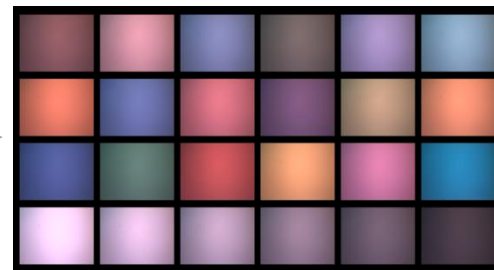
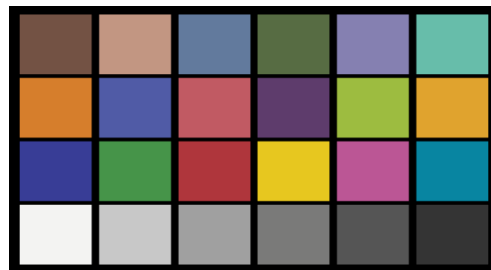


# Semi-Parametric Color Reproduction Method for Optical See-Through Head-Mounted Displays

Yuta Itoh, Maksym Dzitsiuk, Toshiyuki Amano, and Gudrun Klinker

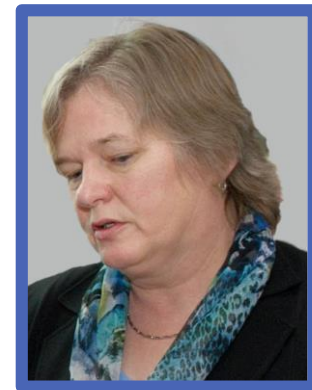
IEEE ISMAR 2015, 30<sup>th</sup> Sep. 2015



# Semi-Parametric Color Reproduction Method for Optical See-Through Head-Mounted Displays

Yuta Itoh, Maksym Dzitsiuk, Toshiyuki Amano,  
and Gudrun Klinker

IEEE ISMAR 2015, 30<sup>th</sup> Sep. 2015



# Head-Mounted Displays (HMDs)

## Non Optical See-Through



## Optical See-Through (OST-HMD)



# Toward consistent AR experience



Aittala, M. *"Inverse lighting and photorealistic rendering for augmented reality"*, Visual Computer. Vol. 26 (2010) No: 6 - 8, 669 - 678.

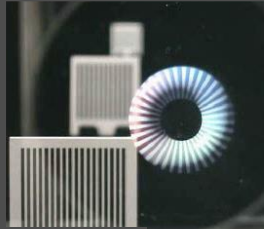
# Consistent AR with **OST**-HMDs

## Visual

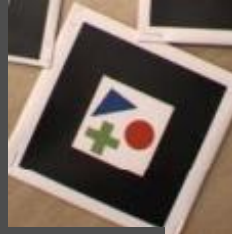


D) Final result

[Kiyokawa '01]

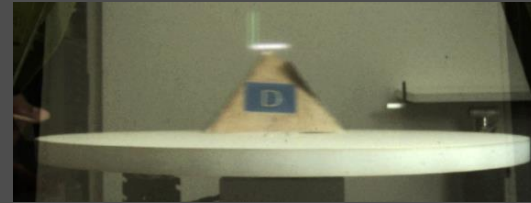


[Liu '08]

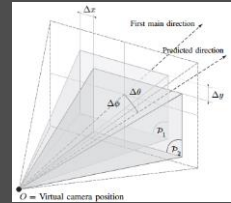


[Lee '09]

## Temporal

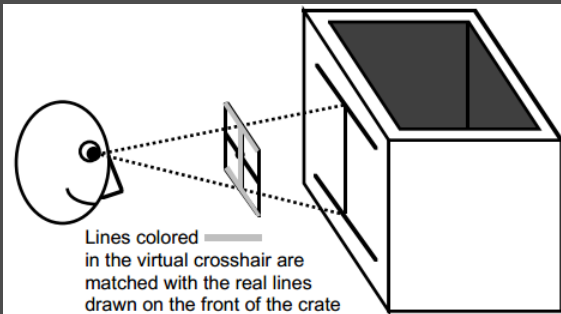


[Zheng '14]

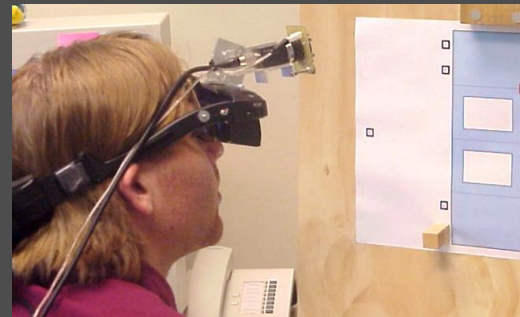


[Didier '05]

## Spatial



[Azuma '95]



[Tuceryan '00] [Genc '02]

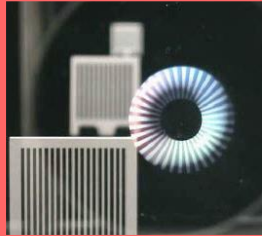
# Consistent AR with **OST**-HMDs

## Visual



D) Final result

[Kiyokawa '01]

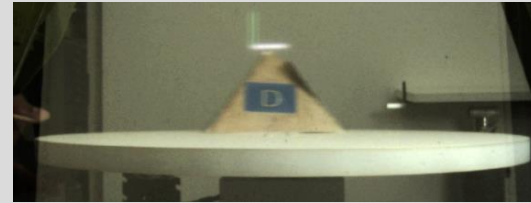


[Liu '08]

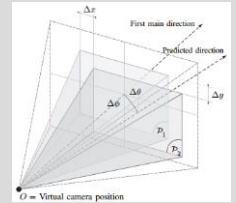


[Lee '09]

## Temporal

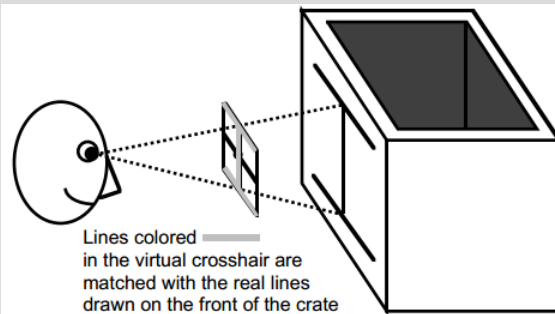


[Zheng '14]

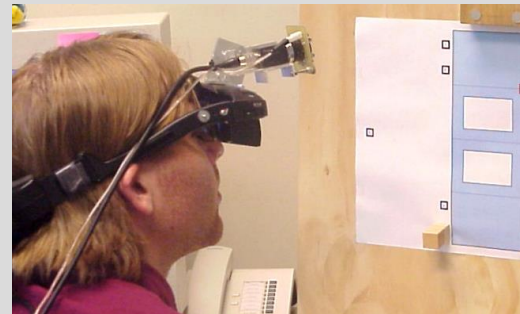


[Didier '05]

## Spatial



[Azuma '95]



[Tuceryan '00] [Genc '02]

# Here is an apple



# We love apples, let's duplicate

Real



Virtual on HMDs





# Color distortion on displays

Real



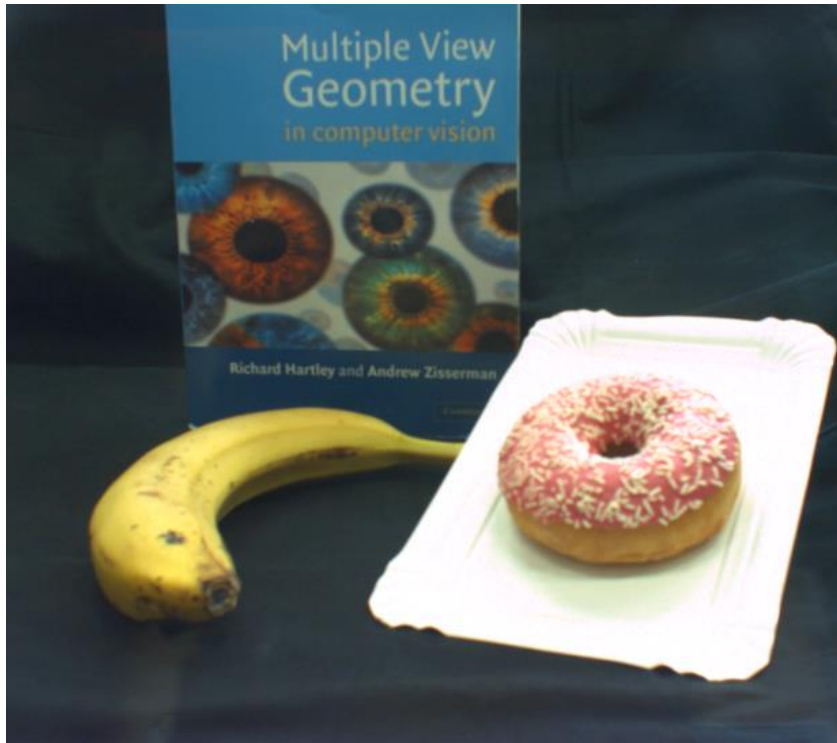
Virtual on HMDs



a.k.a, **color constancy** or **photometric uniformity**

# A real example

Real scene



Virtual on HMDs



# A real example

Real scene

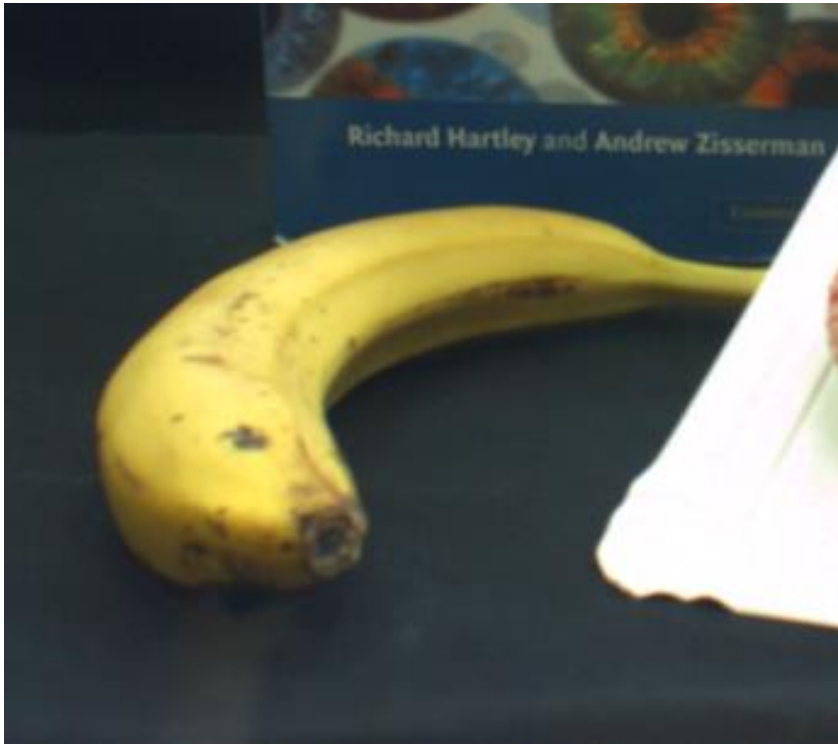


Virtual on HMDs



# A real example

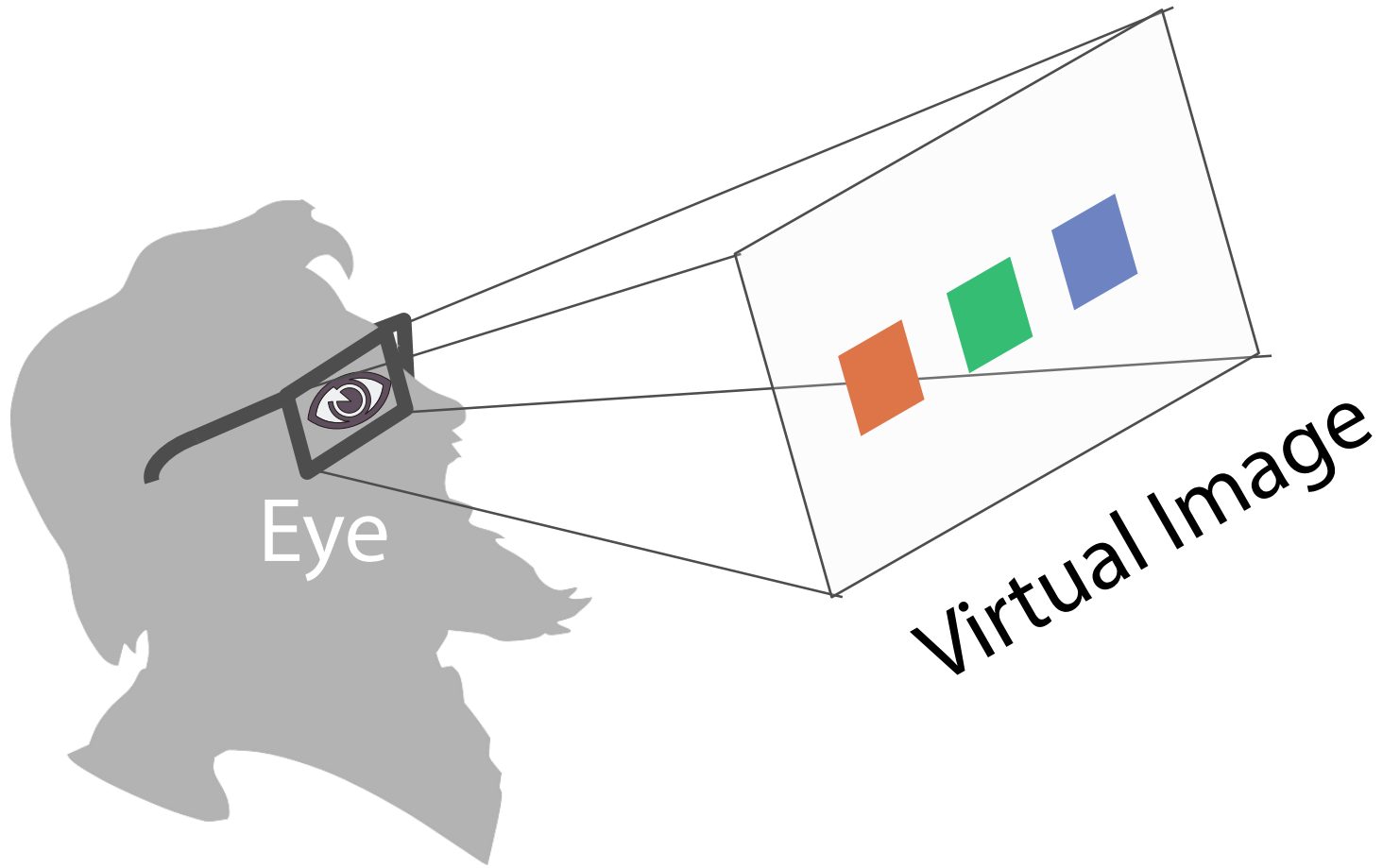
Real scene



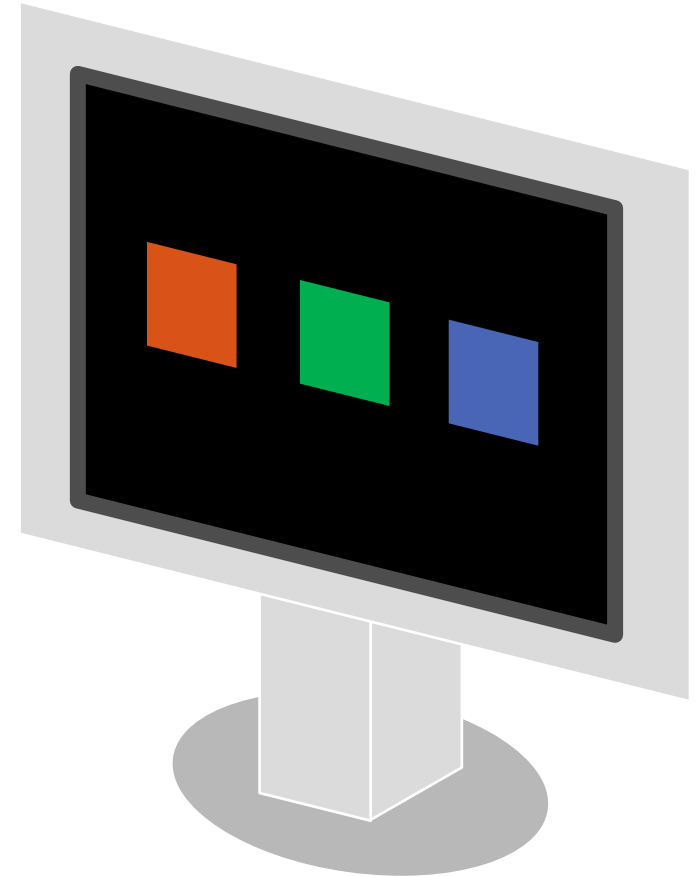
Virtual on HMDs



# (Optical See-Through) HMDs

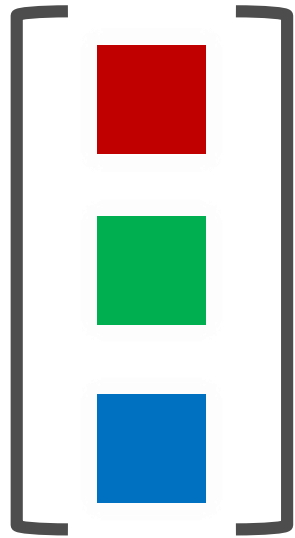


# Analogy to conventional displays

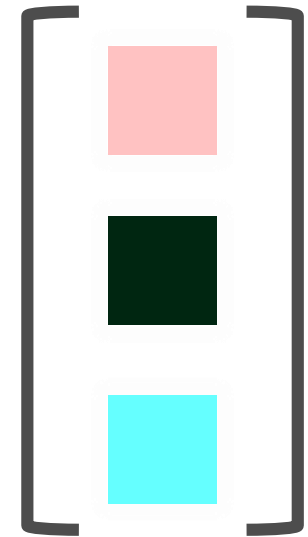


# Display (HMD)

Input



Output



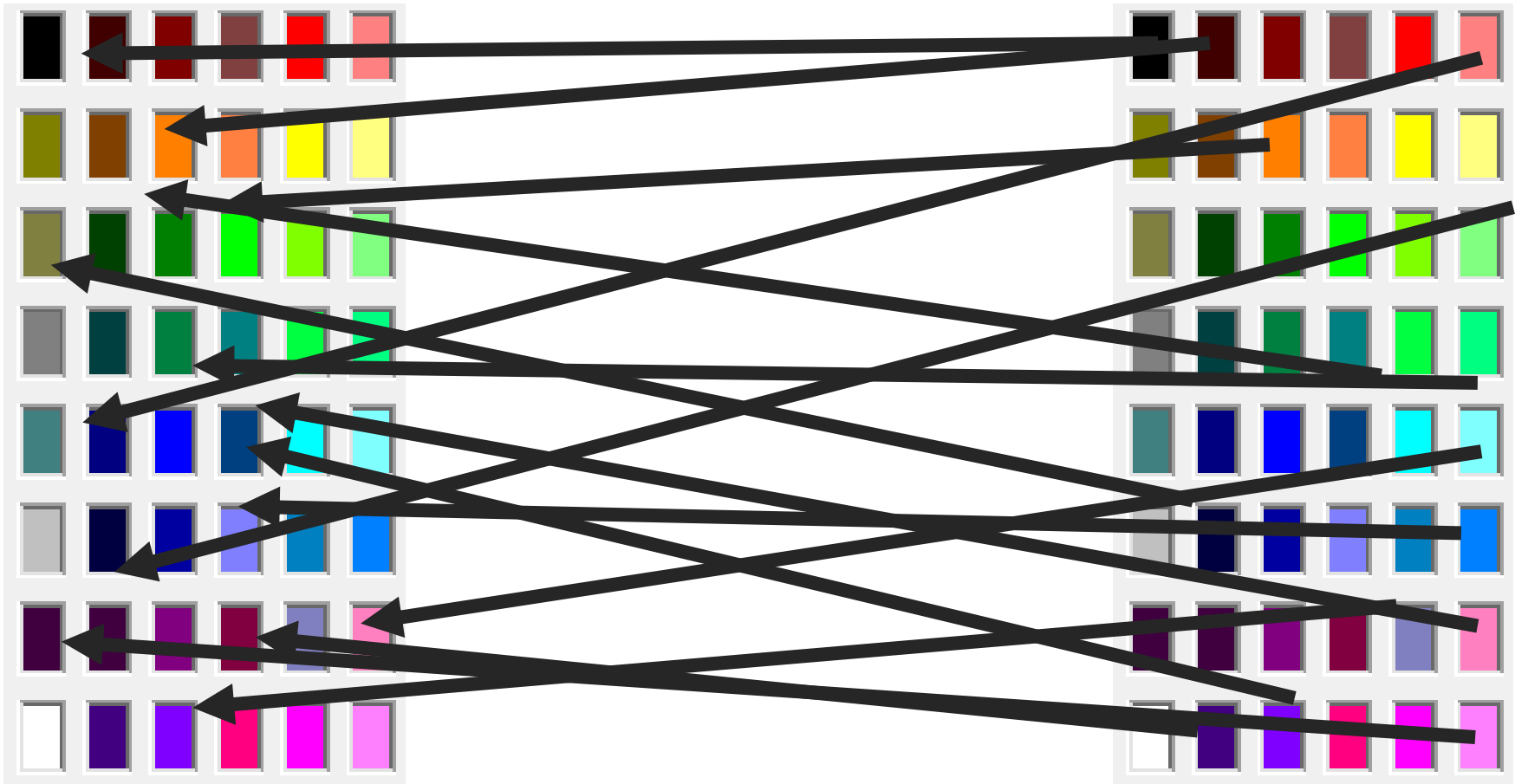
# Strategy 1: Non-parametric

## Look-Up Table (LUT)



Input

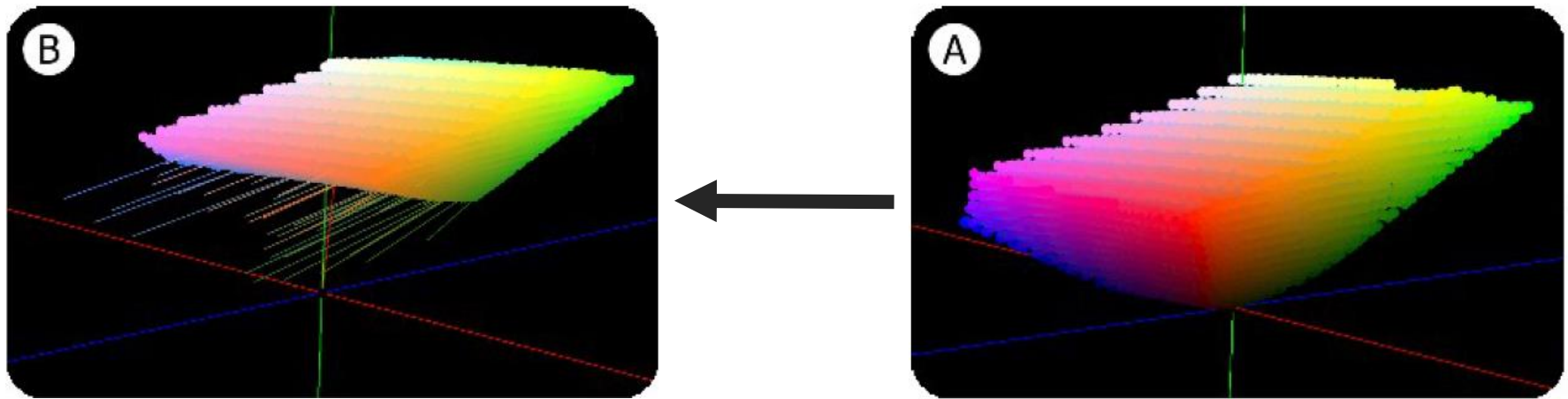
Output





# Strategy 1: Non-parametric

- **Binned** Look-Up Table (LUT)
- Binary-tree search



J. David Hincapié-Ramos, L. Ivanchuk, S. K. Sridharan, and P. Irani, “**Smartcolor: Real-time color correction and contrast for optical seethrough head-mounted displays**,” in Proc. ISMAR. IEEE, 2014, pp. 187–194.

# Strategy 1: Non-parametric

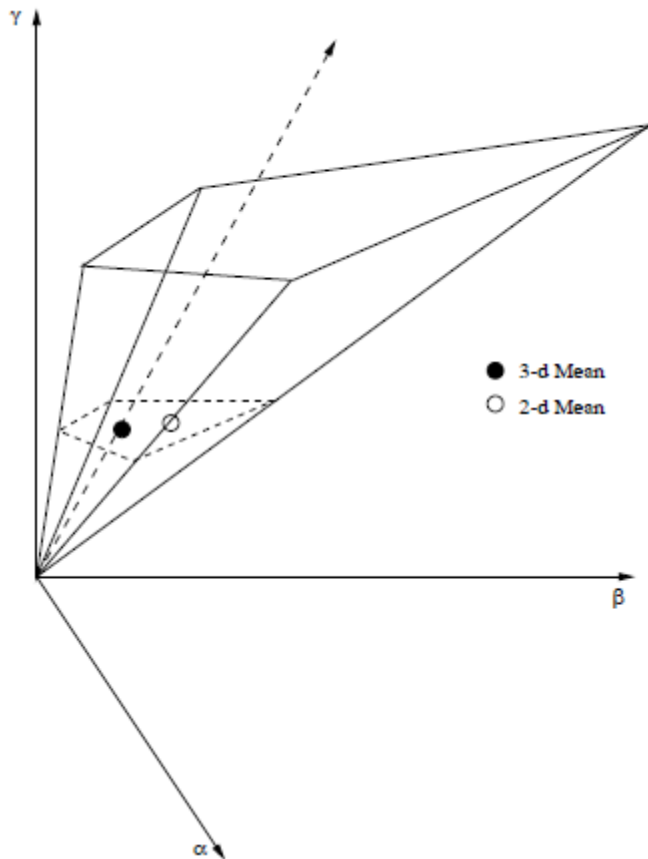
Application in Spatial AR  
(12x12x12 grids, GPU impl.)



C. Menk and R. Koch, "Truthful color reproduction in spatial augmented reality applications," *Visualization and Computer Graphics, IEEE Transactions on*, vol. 19, no. 2, pp. 236–248, 2013

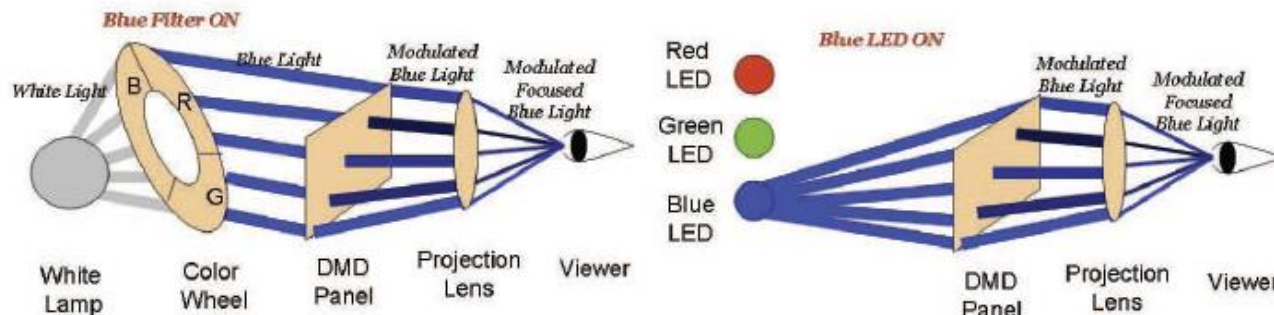
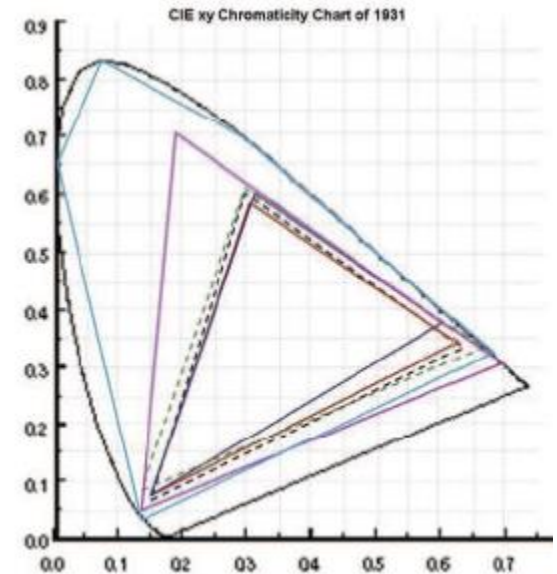
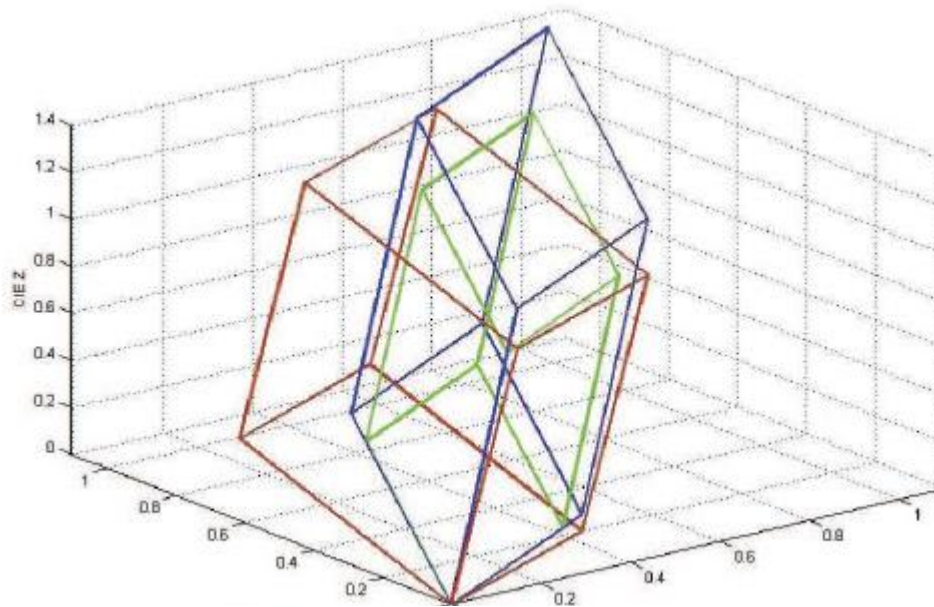
# Strategy 2: Parametric model

Color Gamut Mapping [Finlayson '01]  
[Forsyth '90]

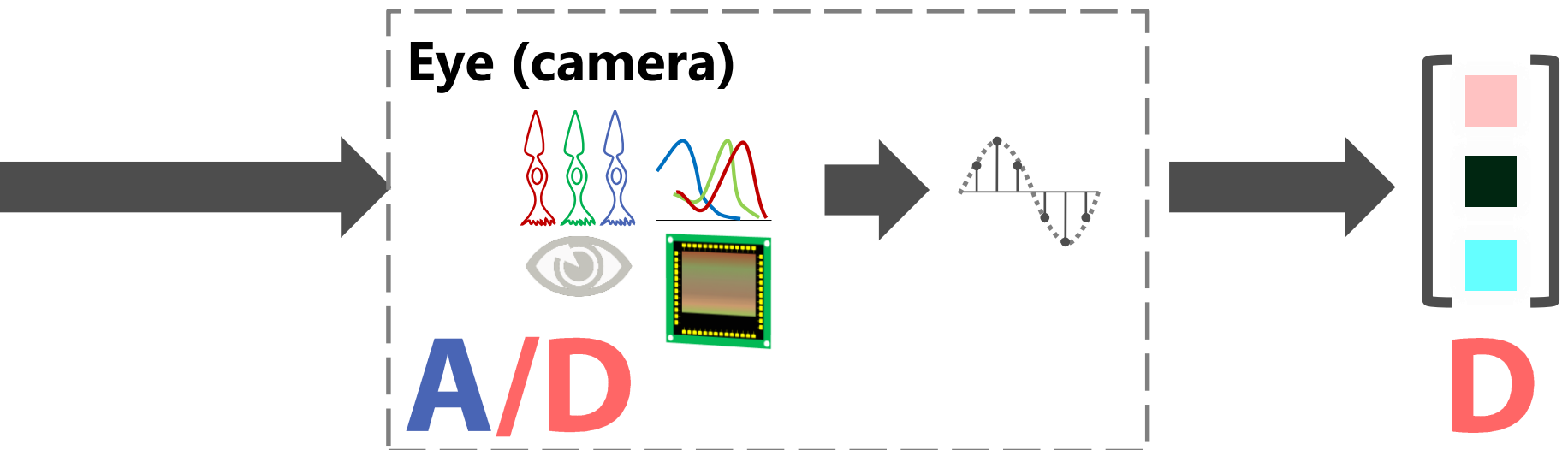
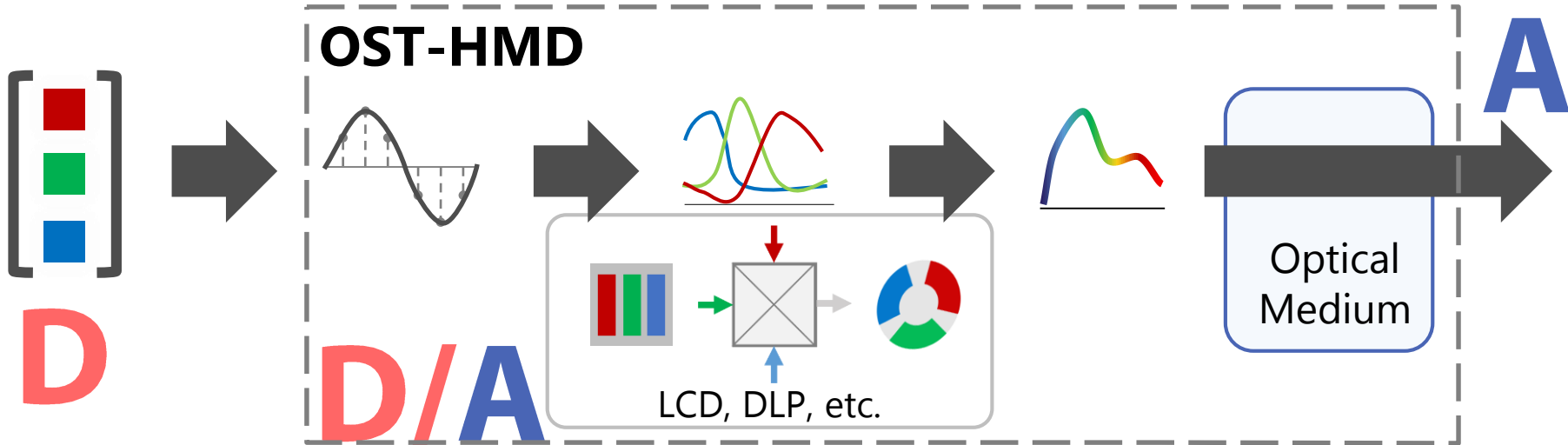


# Strategy 2: Parametric model

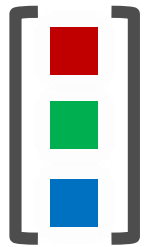
## Color Gamut Mapping [Majumder '10]



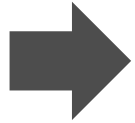
# Digital <--> Analog conversions



# Dominant distortion factors



$D$



OST-HMD

**Non-linear** distortion

$D/A$

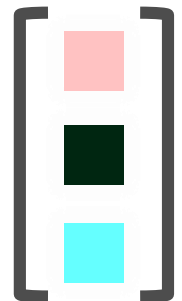
$A$



Eye (camera)

**Color mixing**

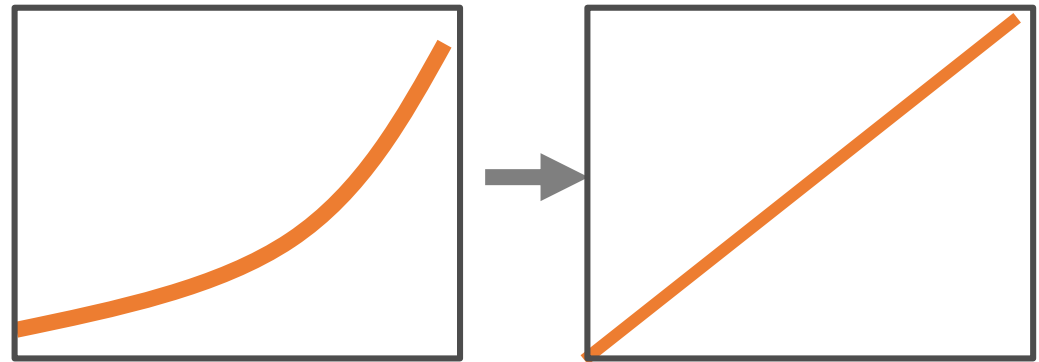
$A/D$



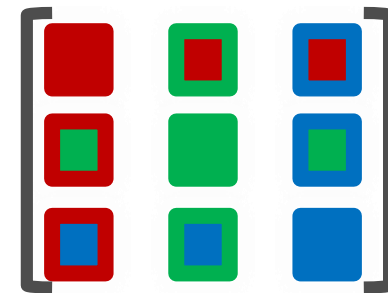
$D$

# Strategy 3: Semi-parametric

- **Non-linear** Gamma correction



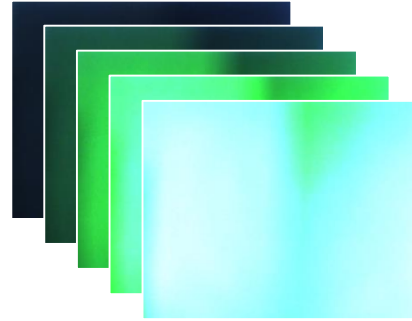
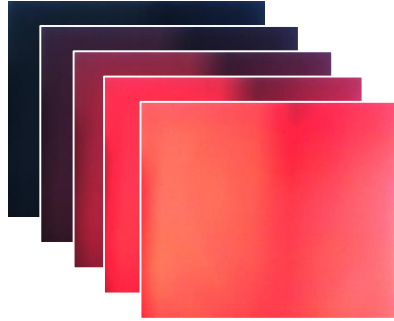
- **Color mixing** matrix  
(3x3 matrix)



S. K. Nayar, H. Peri, M. D. Grossberg, and P. N. Belhumeur, "A projection system with radiometric compensation for screen imperfections," in ICCV workshop on projector-camera systems (PROCAMS), vol. 3. Citeseer, 2003.

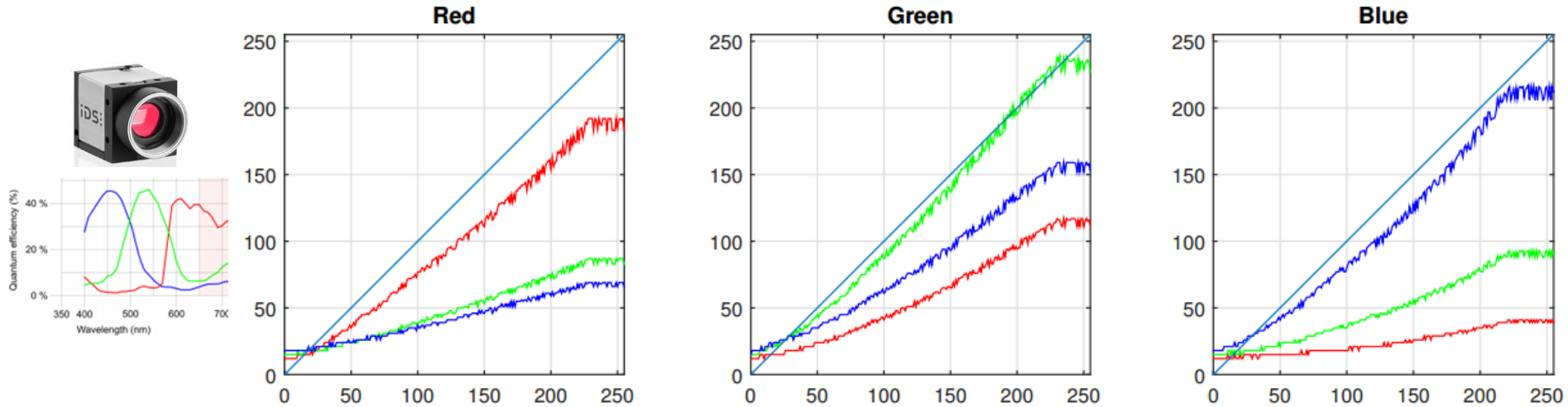
# Channel-wise color measurements

HMD



User view

$O(n^*3)$ , not  $O(n^{\wedge}3)$ ,  $n=256$

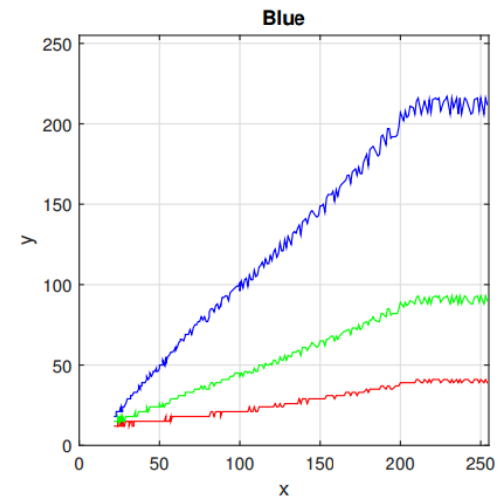
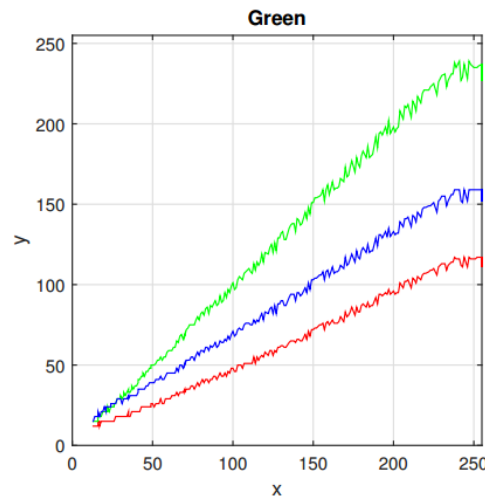
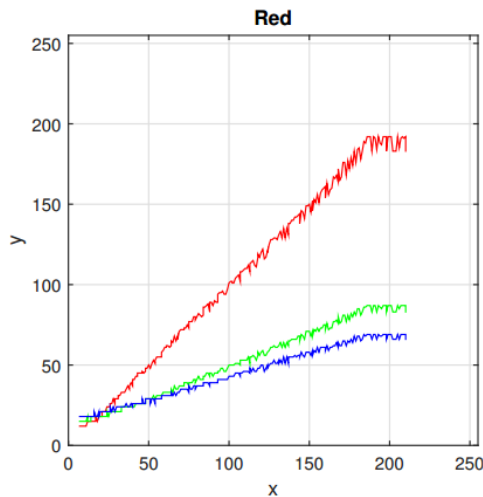


Color mixing & non-linearity

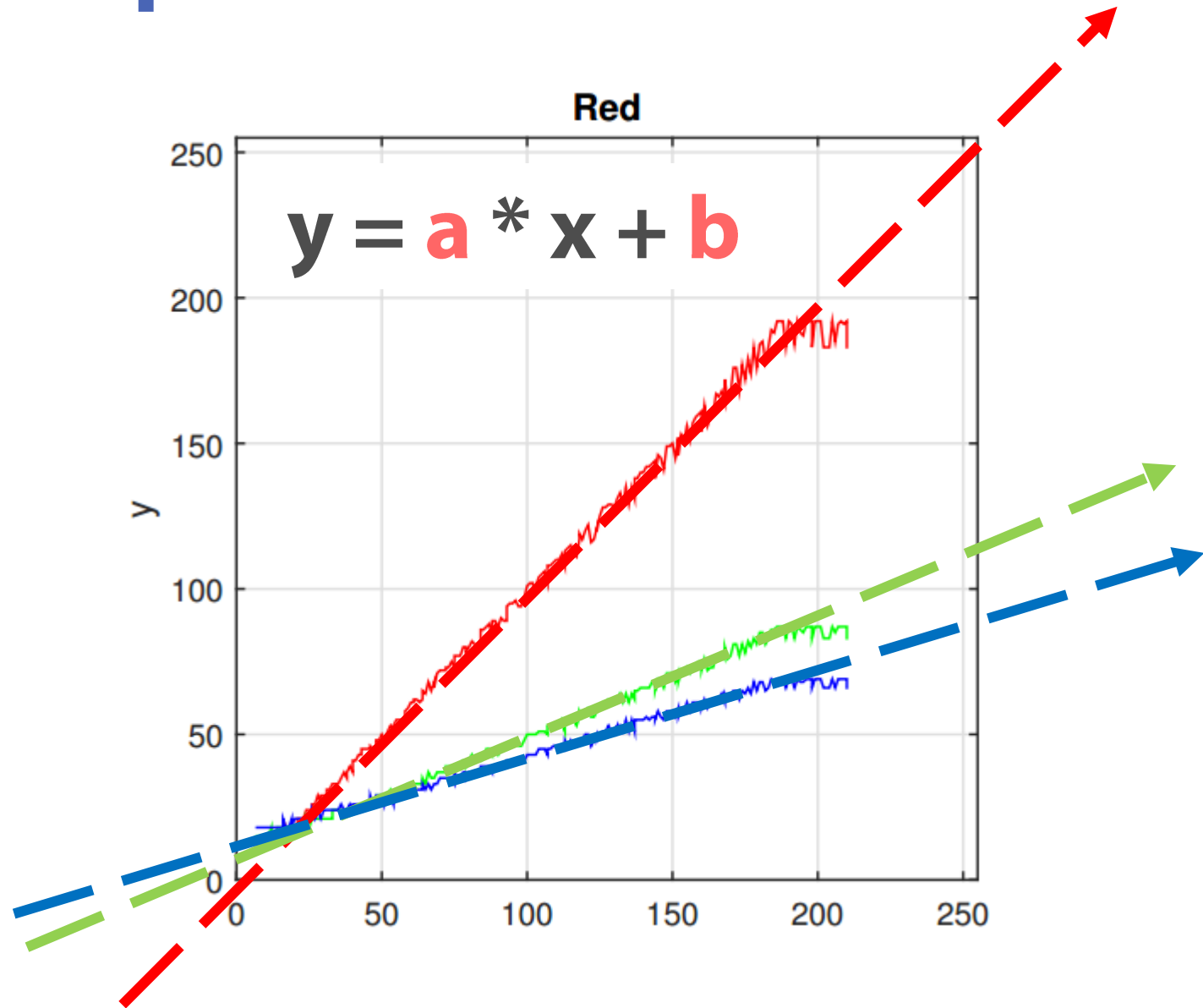


# Linearize channel wise distortions

Learn three **Gamma** functions  $g$   
(**non-linear** part)

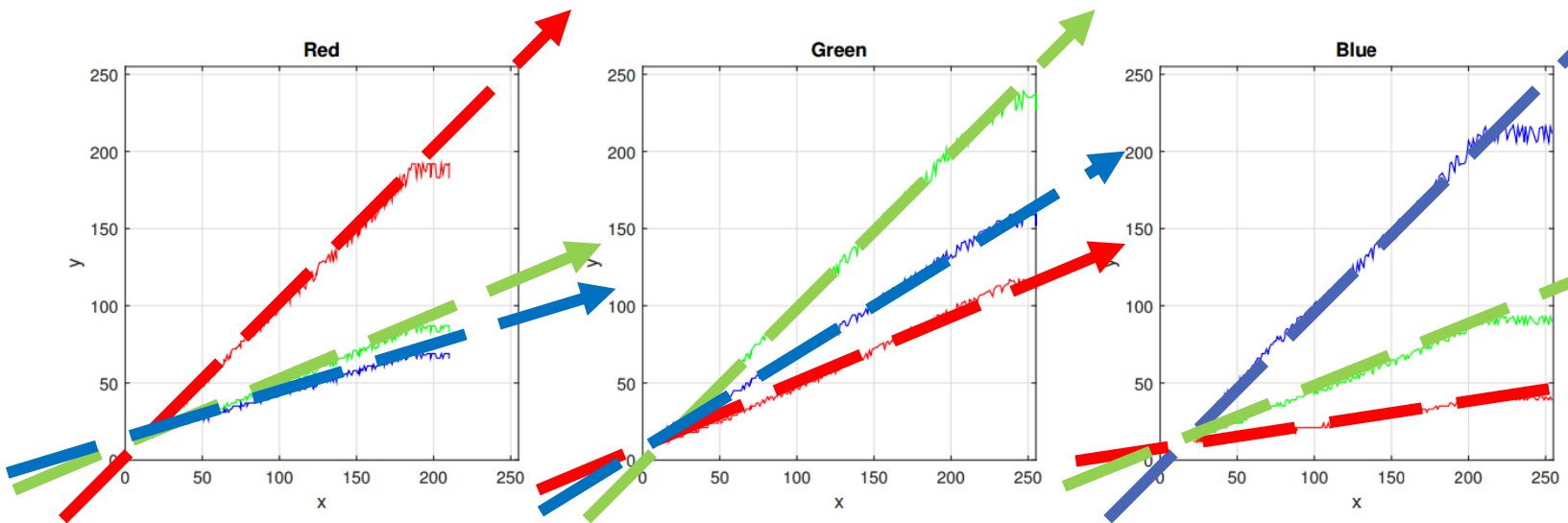


# Linearized plot



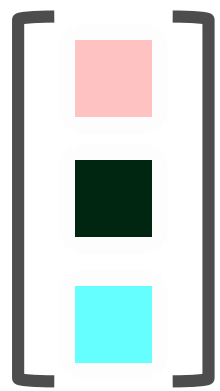
# Color mixing matrix

Each line can be modeled as linear lines

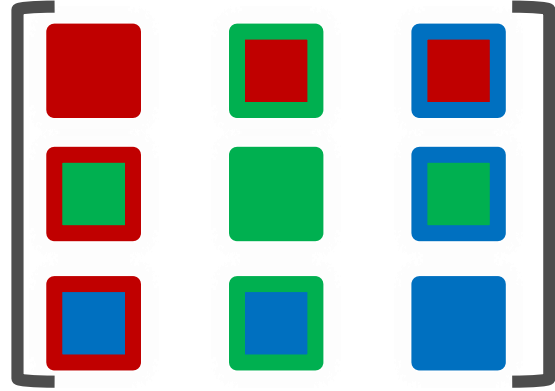


# Color mixing matrix

Required  
input



=



Color mixing  
matrix

$-1$   
 $*$

Linearized  
Input

$-1$

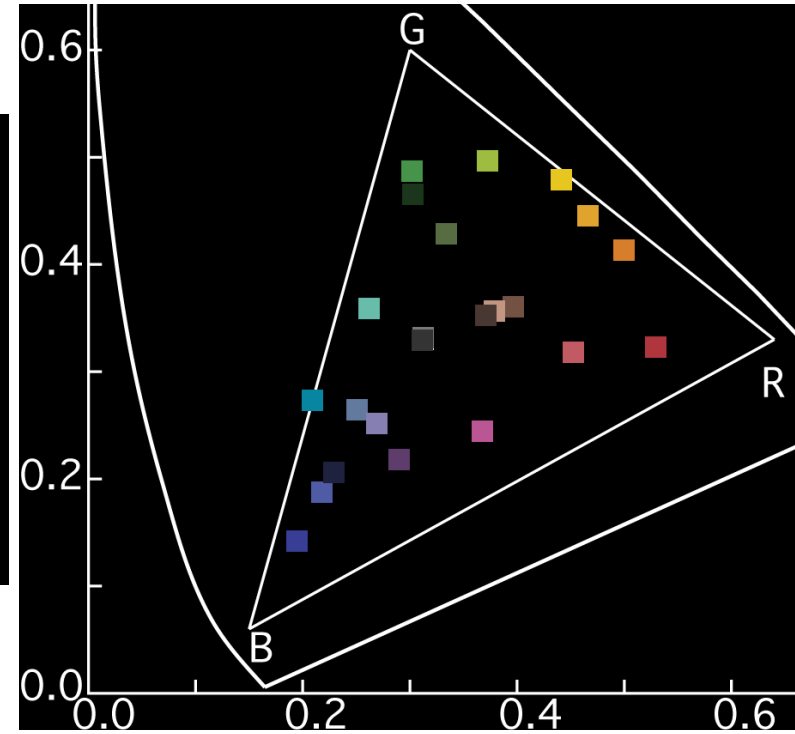
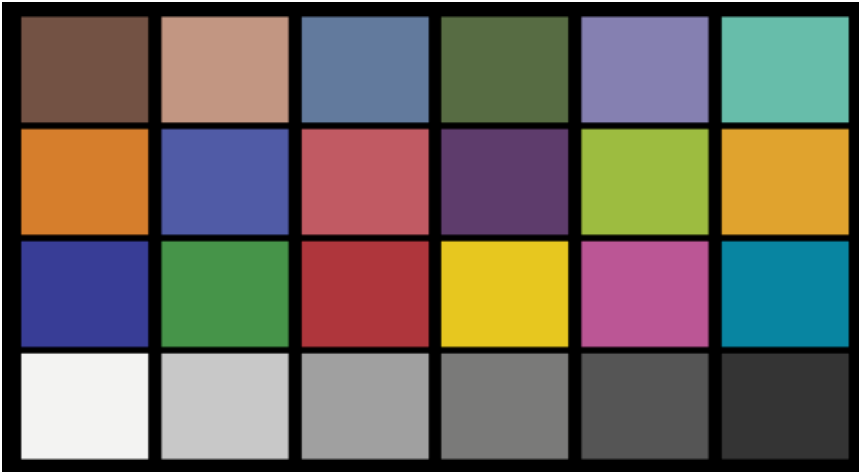
$g$

gamma

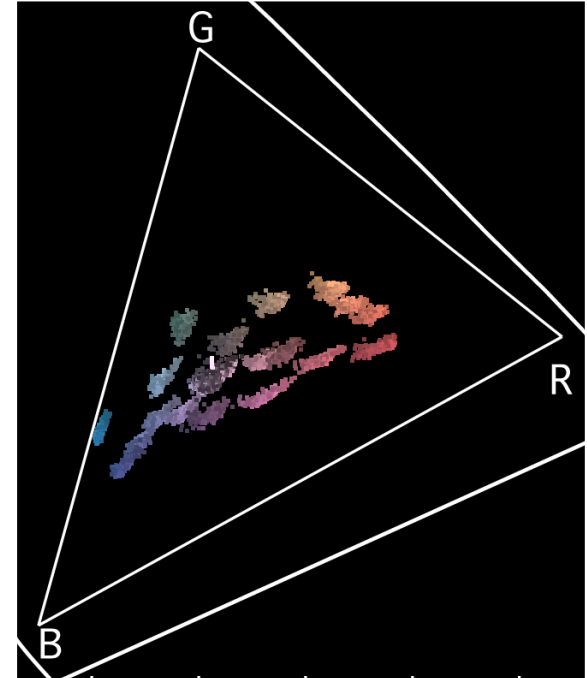
# Evaluation setup: HMD + Camera



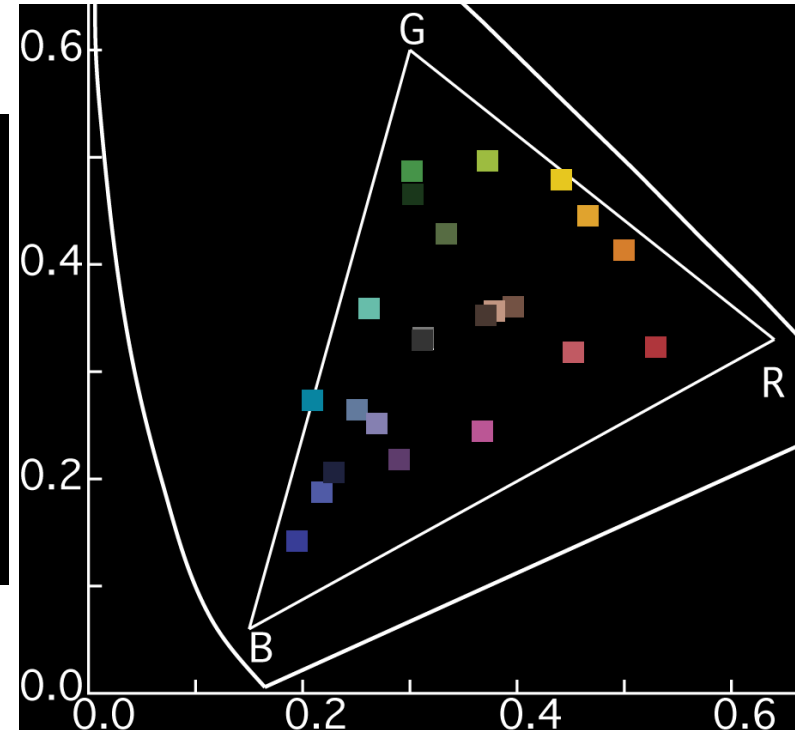
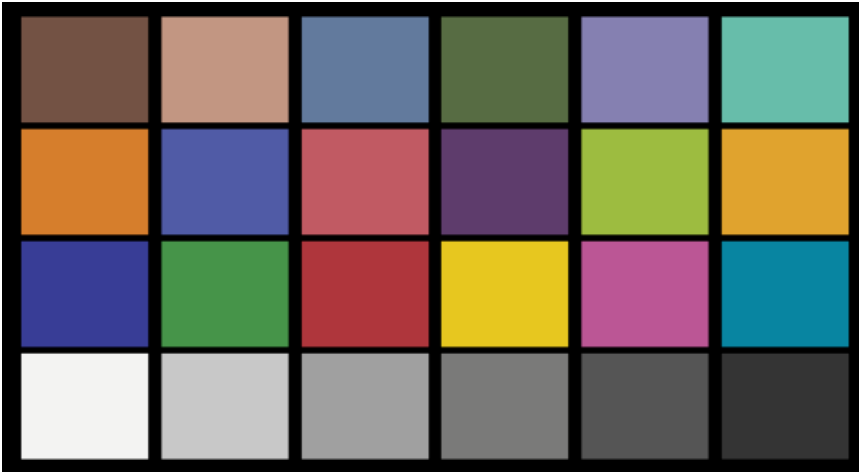
# Target output



# Output, no-correction

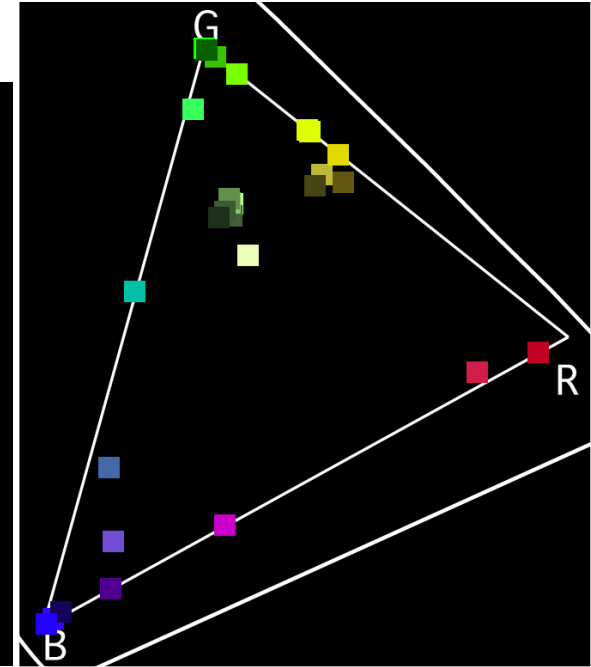
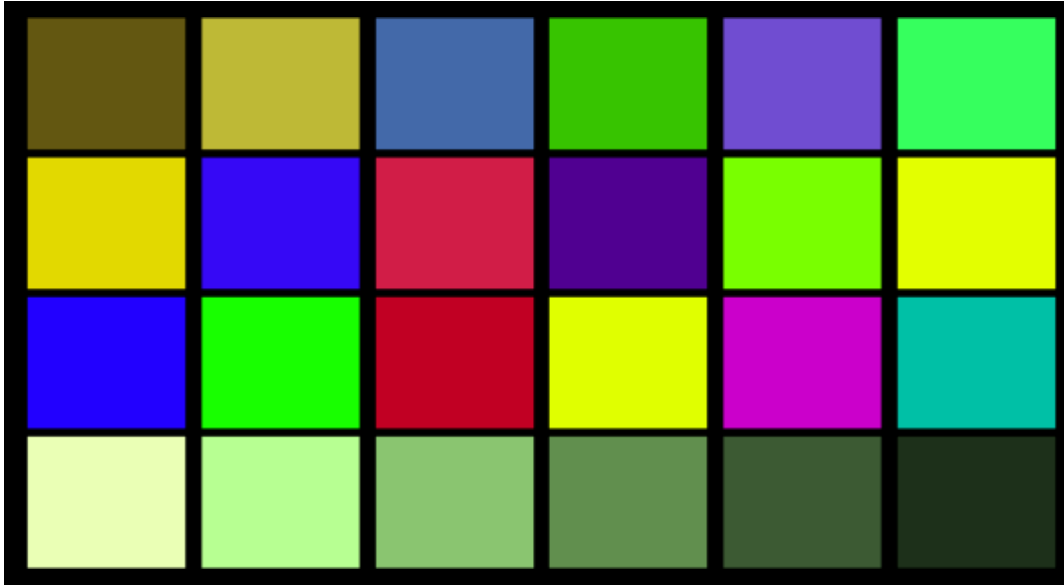


# Target output

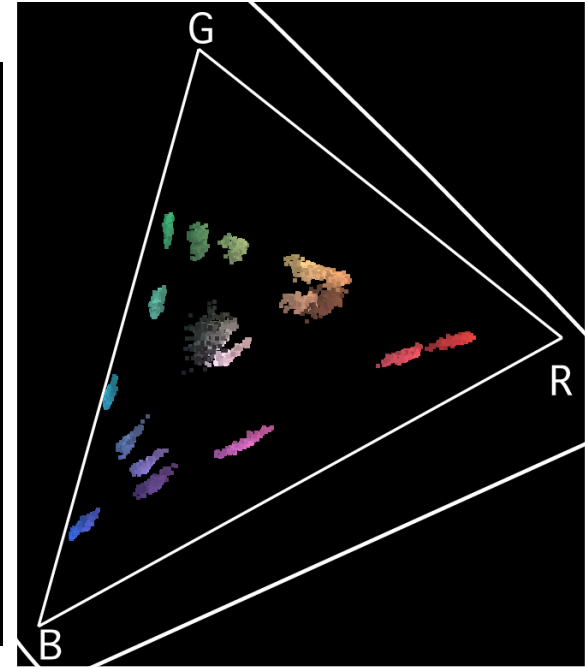




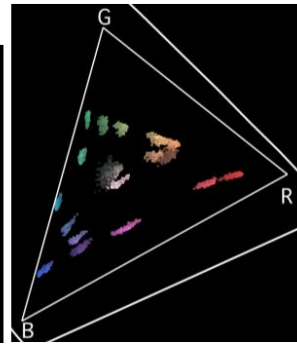
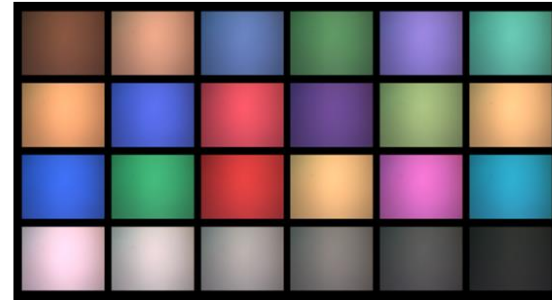
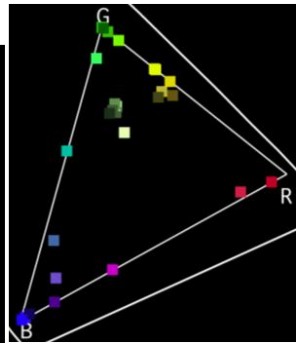
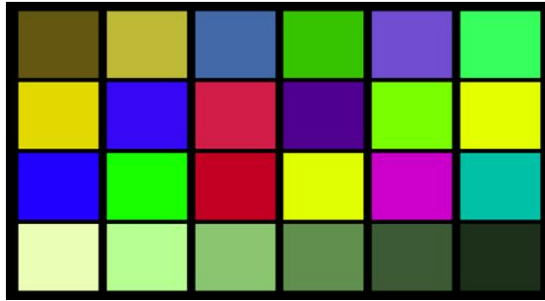
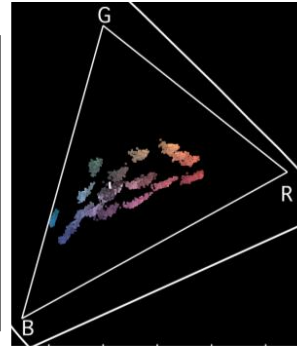
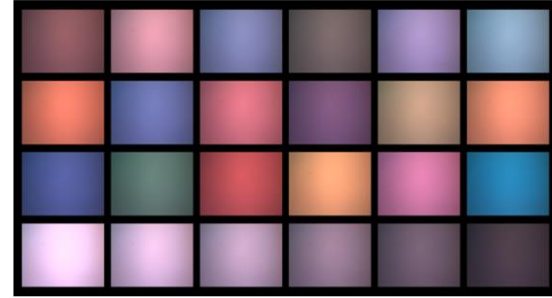
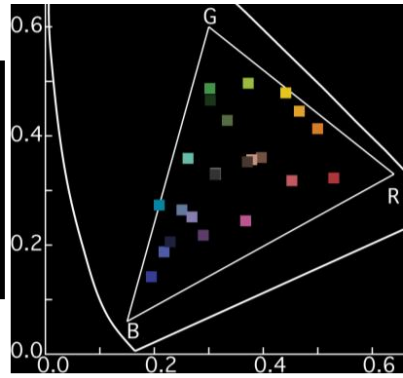
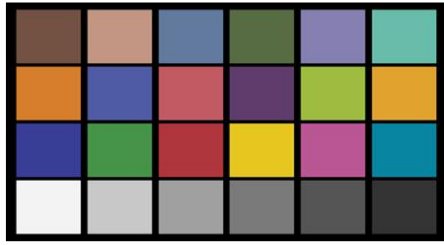
# Pre-corrected input



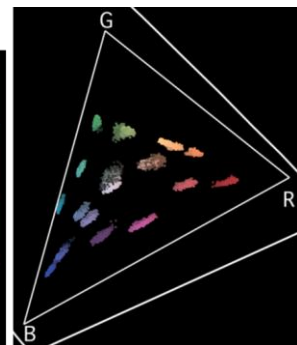
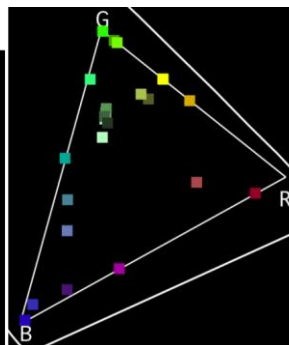
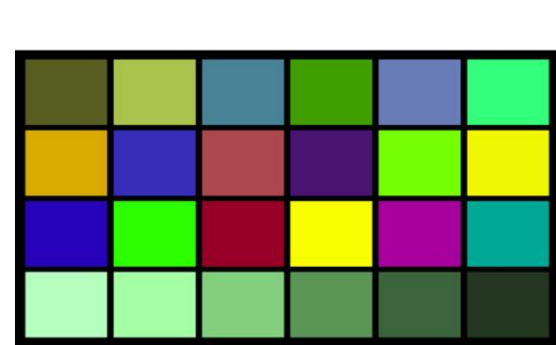
# Output, corrected



# Target



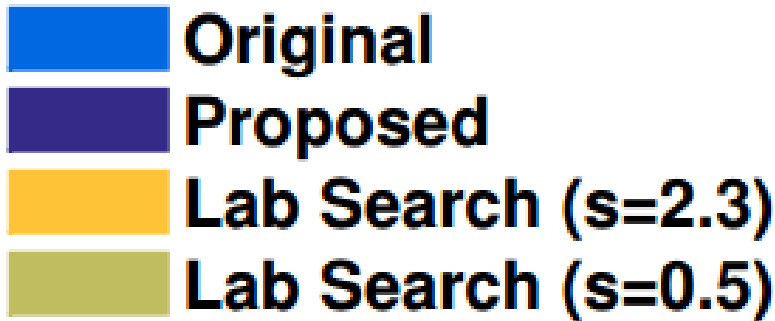
# Baseline (LUT)



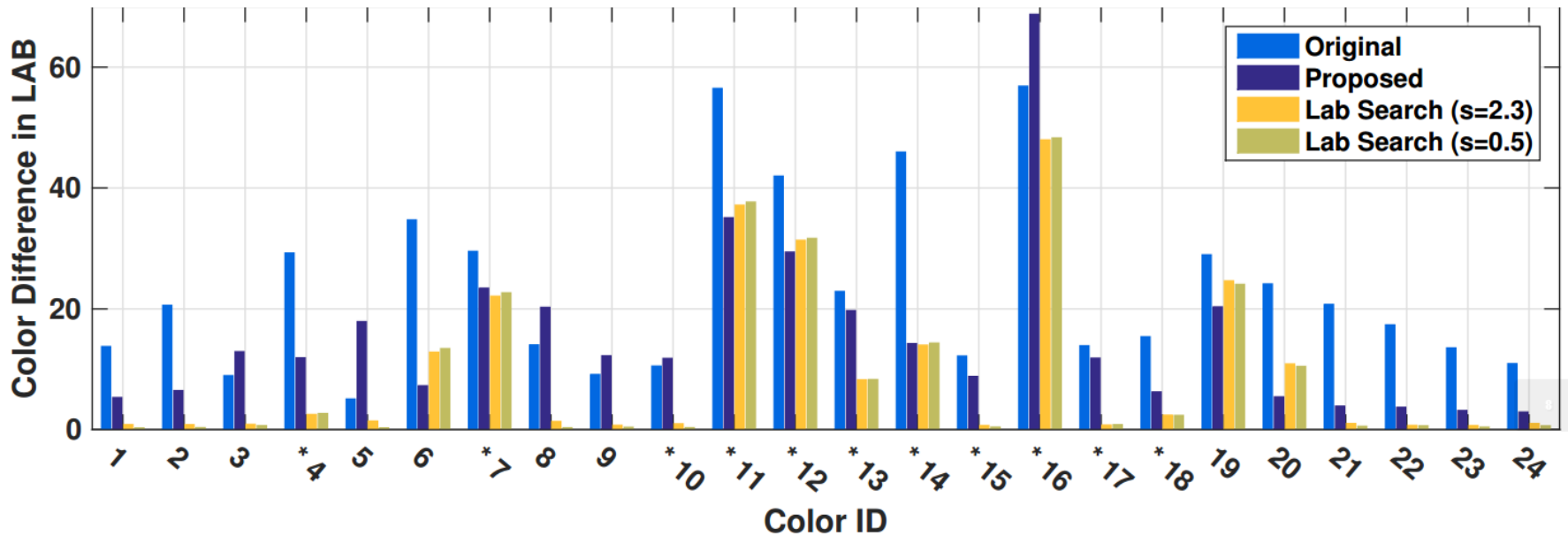
# Corrected

# Errors in Lab space

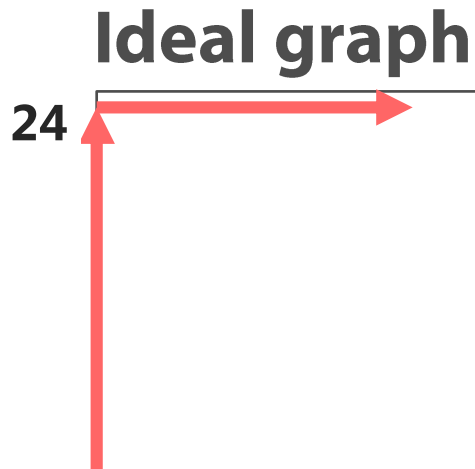
1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24



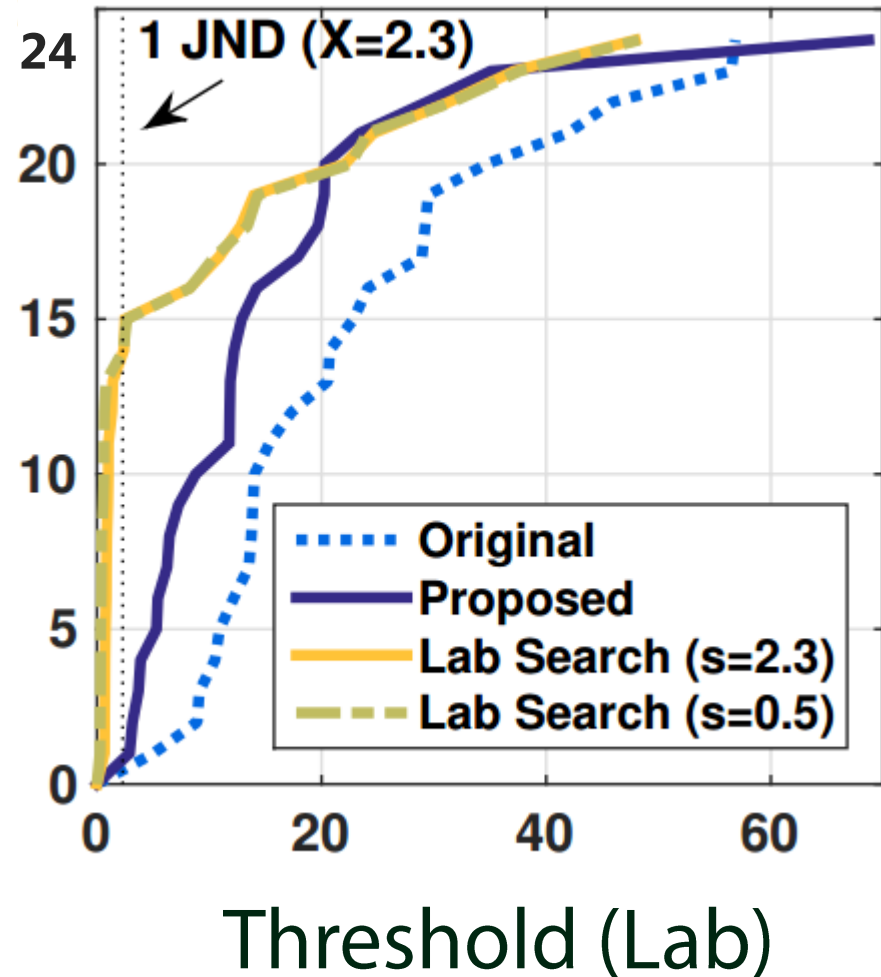
} Baseline (LUT)



**How many** colors  
lower than the  
threshold?



Just Noticeable Distance  
(JND)

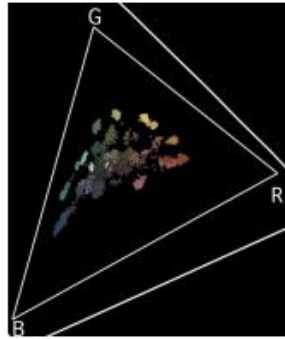
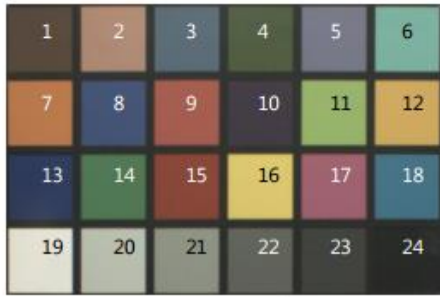


# Real color chart with HMD 1

Target

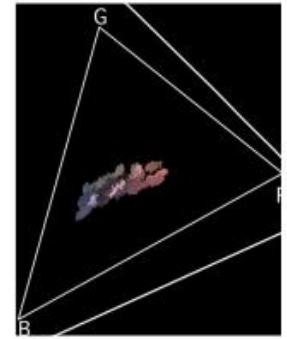


Original input

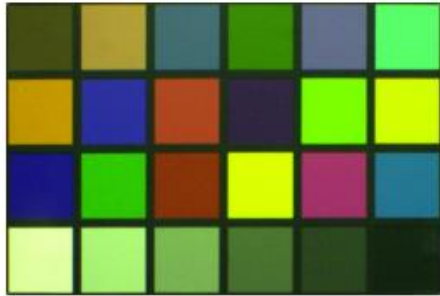


Display

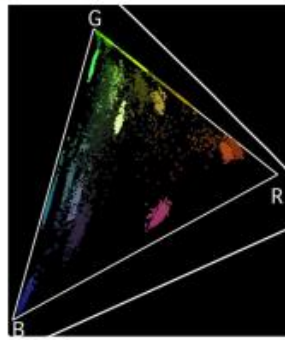
Original, measured



Calibrated input

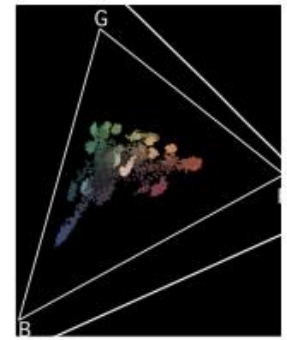


Color correction



Display

Calibrated, measured



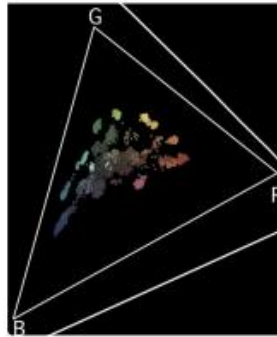
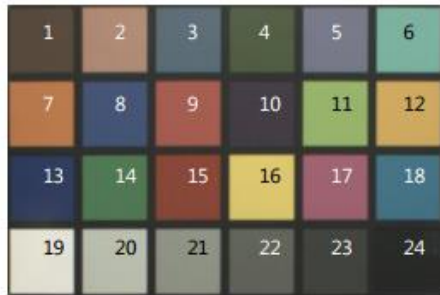
Observed,  
corrected

# Real color chart with HMD 2

Target

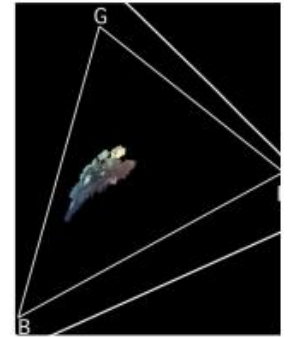


Original input



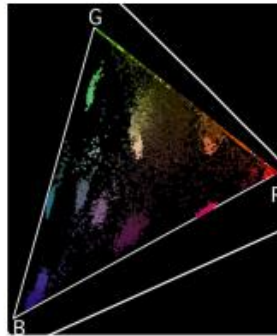
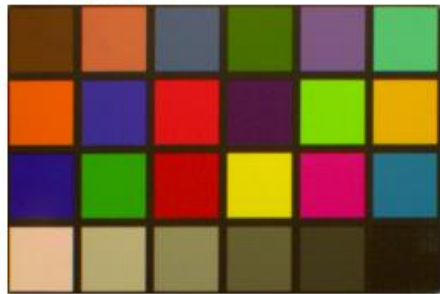
Display

Original, measured



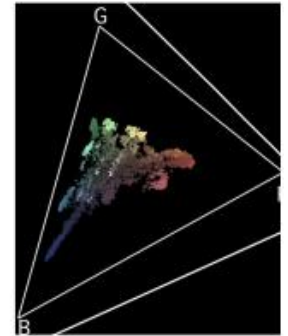
Color correction

Calibrated input



Display

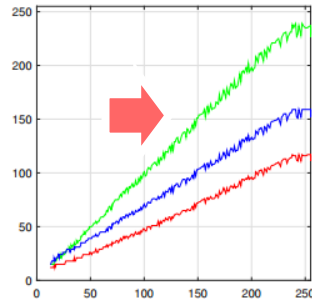
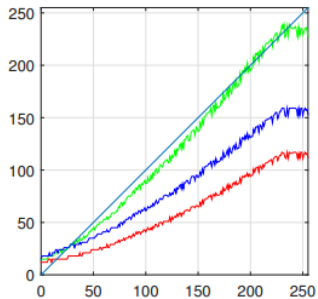
Calibrated, measured



Observed,  
corrected

# Summary

- Maintaining **Color constancy** is important in **(OST-)HMDs**
- Providing a **semi-parametric** model for color correction
- What the best way to model HMD colors?



$$\begin{bmatrix} \text{red} \\ \text{green} \\ \text{blue} \end{bmatrix} = \begin{bmatrix} \text{red} & \text{green} & \text{blue} \\ \text{red} & \text{green} & \text{blue} \\ \text{red} & \text{green} & \text{blue} \end{bmatrix}^{-1} * g^{-1} \left( \begin{bmatrix} \text{red} \\ \text{green} \\ \text{blue} \end{bmatrix} \right) + \begin{bmatrix} \text{red} \\ \text{green} \\ \text{blue} \end{bmatrix}$$





# Appendix

# Black offset

$$y = a * x + b$$

