Visual Display Calibration

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Colourlab

COSI Computational Colour and Spectral Imaging

Outline

INTRODUCTION

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- Objective
- Approach
- Workflow

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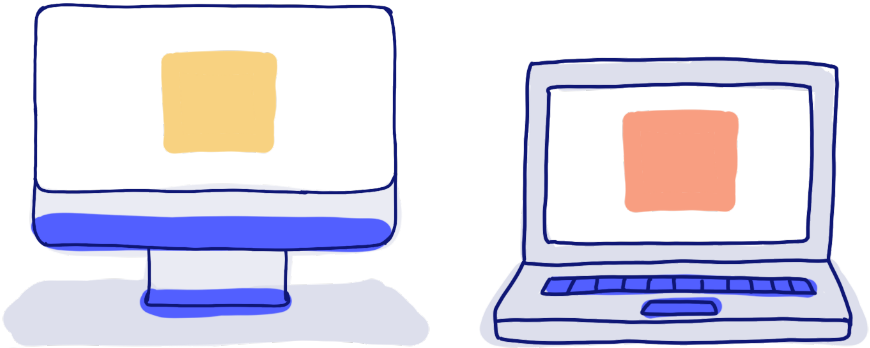
- Future Work

Introduction

- *Problem & Motivation*
- *Objectives*
- *Approach*
- *Workflow*

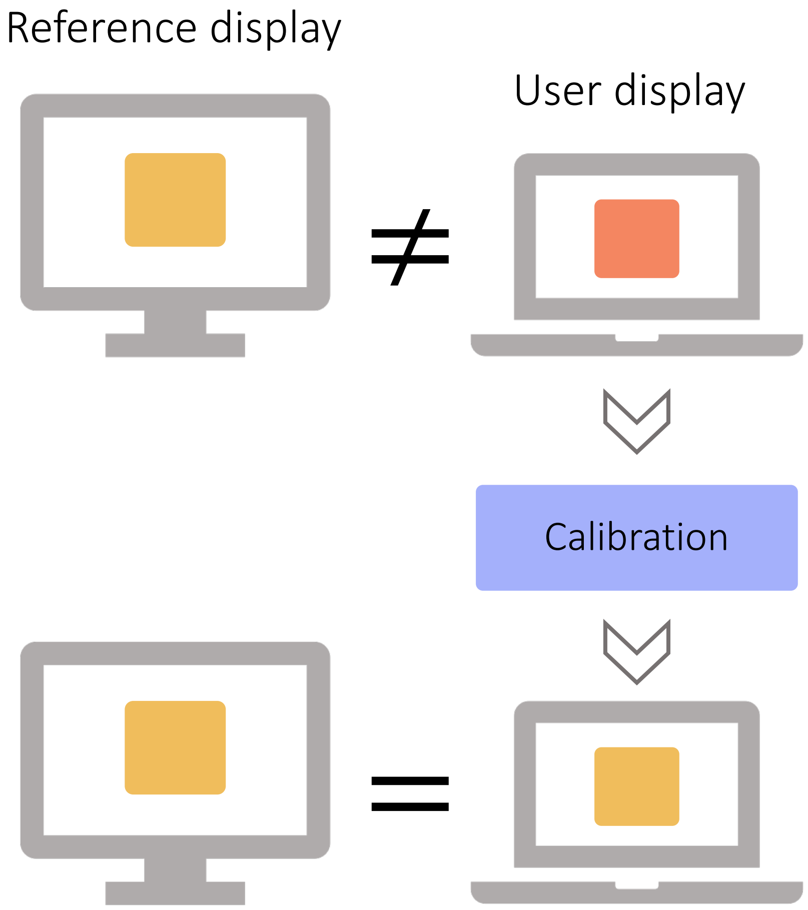


Problem & Motivation

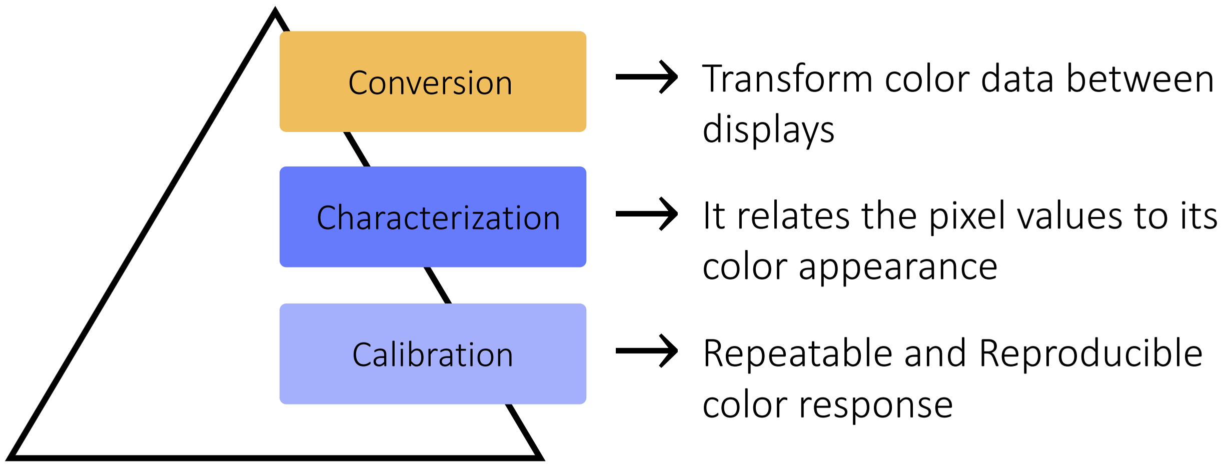
Color Accuracy between displays challenges

- Online Communication increases color accuracy importance
- COVID-19: Face to face activities are moved online
- Selling web products: the color of the product should match on display
- Inversive clothing VR wear, XR clinical education, VR Museums

Display Calibration



- Addressed by calibration
  - Measuring devices:
    - Expensive
    - Not available for every user
  - Visual calibration:
    - Focus on parameters such as contrast or luminance
    - Not focus on colorimetric calibration



Objective

Study a Solution to the color mismatch

Color appearance preservation across displays

Use Human judgments rather than an external measurement instrument

Focus on colorimetric calibration on the web

Improve Visual Display Calibration

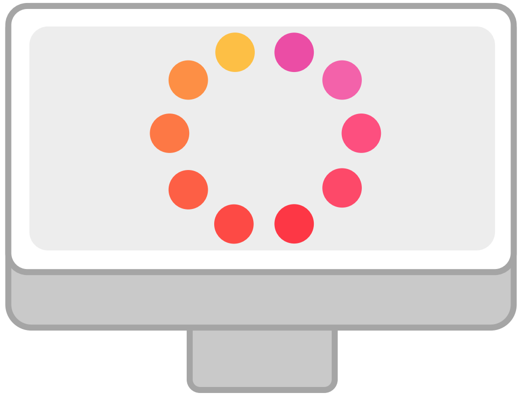
Visual Colorimetric Calibration approaches

Visual judgment-based colorimetric calibration approaches in the literature:

- Matching a display color with a physical reference → Printed dollar with known colorimetric coordinates

(Mulligan, 2009)

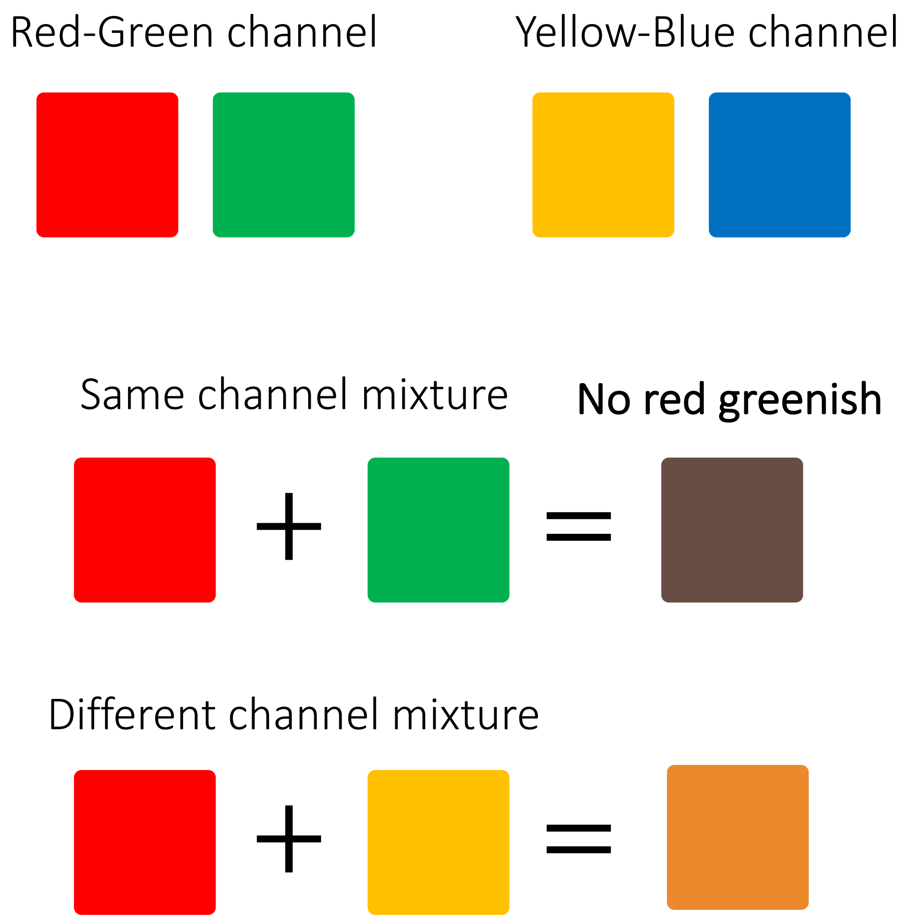
- Concept of **unique hues** to perform visual judgments → Define color properties of the display



(Karatzas and Wuerger, 2007)

Unique hues

- Color appearance mechanism consisting of two pair of hues: red-green and yellow-blue
- No color that can simultaneously contain one of the pairs of hues at the same time
- Four elementary colors: red, green, blue and yellow
- Color calibration using unique hues → they are approximately constant across:
  - Culture
  - Gender
  - Age
  - Race
  - Etc.



Workflow

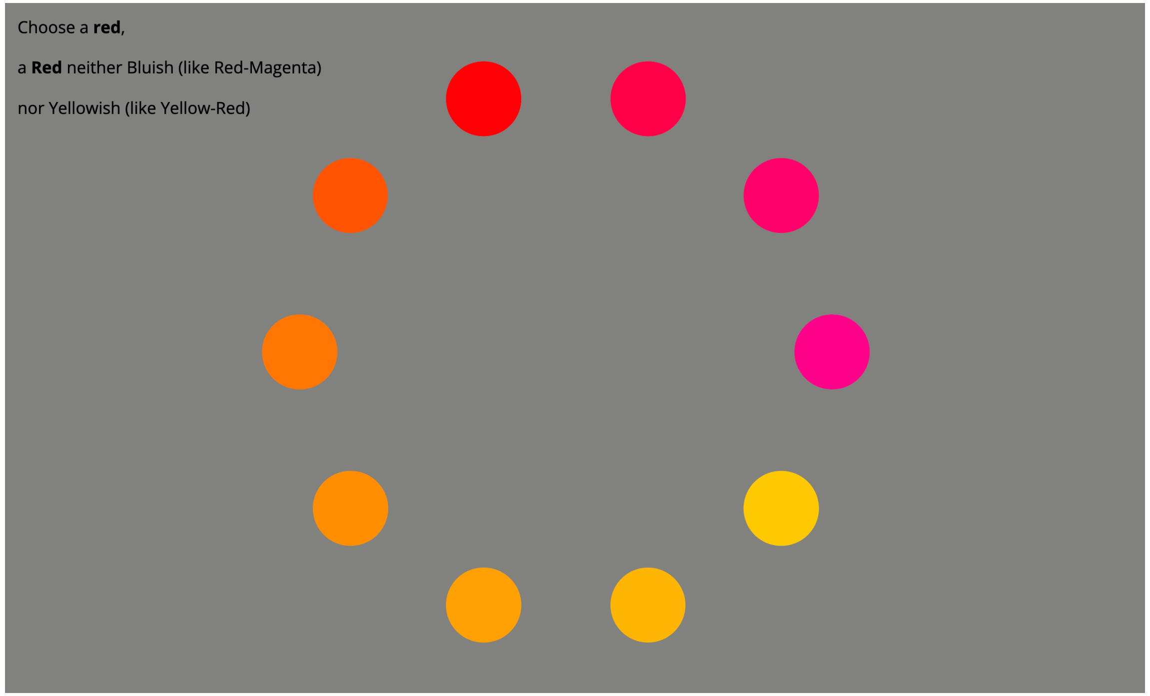
1. Graphical User Interface design — GUI
2. Psychophysical Experiments about selecting unique hues — Data Collection
3. Display profile from the previous experiments which characterizes the display color properties — Calibration File
4. Transformation computed using two device profiles — Matrix-Based Transformation
5. The transformation is applied to convert the pixel values of a display to match another display — Calibration

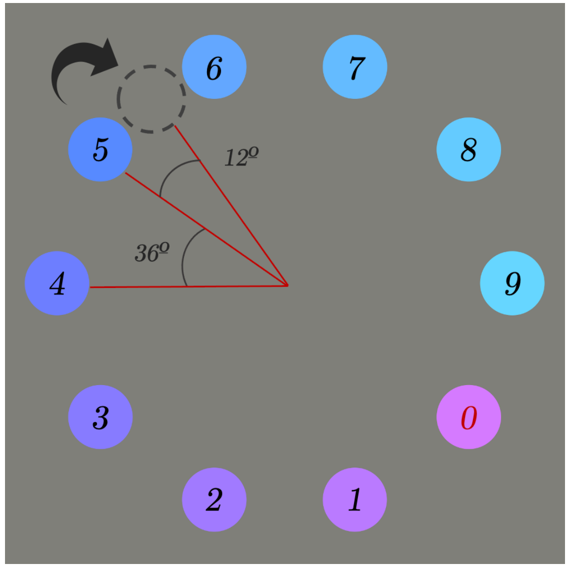
Data Collection

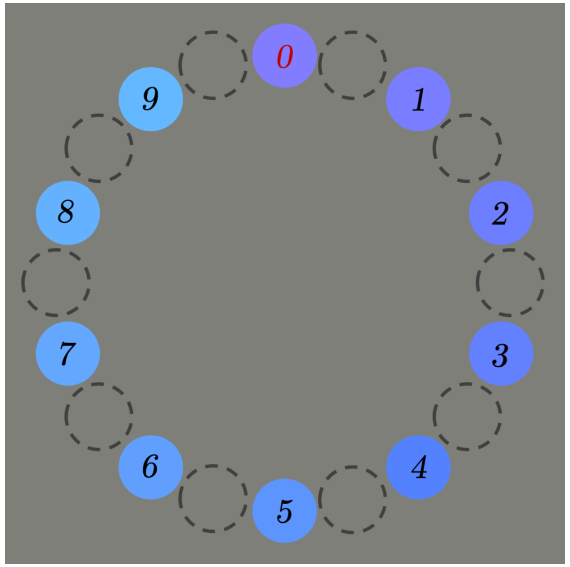
- *Experimental Interface Design*
- *Experimental Methodology*
- *Neutral background stage*
- *Hue selection stage*

Experimental Interface Design

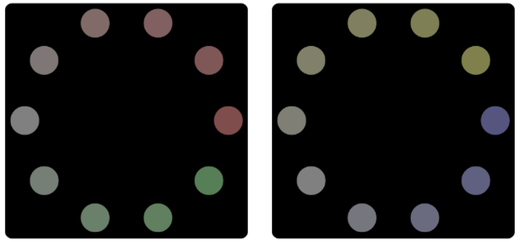
- JavaScript, CSS, html:
  - Avaiable for every device
  - It can be run online
- Stimuli:
  - 10 selectable patches
  - Ordered fashion arrangement
  - At 60 cm: 2^{o} patch diameter, 12^{o} annulus diameter
  - Mouse press to select the patch
- Rotations between trials:
  - Rotation to mitigate sucessive contrast
  - Rotation to cover all screen locations







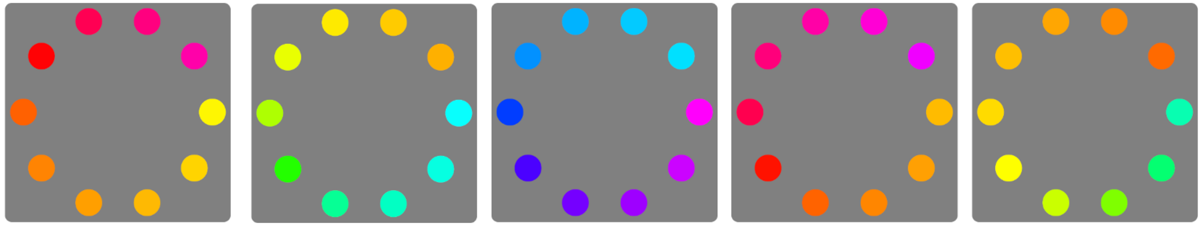
Experimental Methodology



Neutral Grey (First stage)

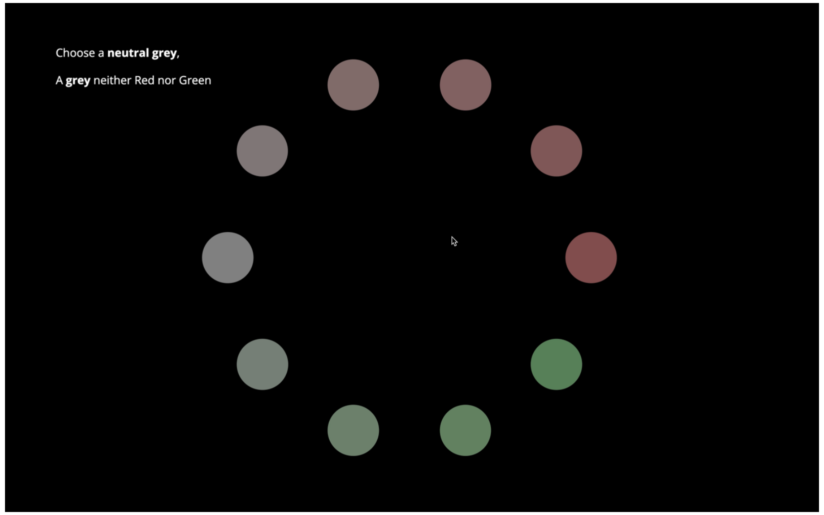
Achromatic background

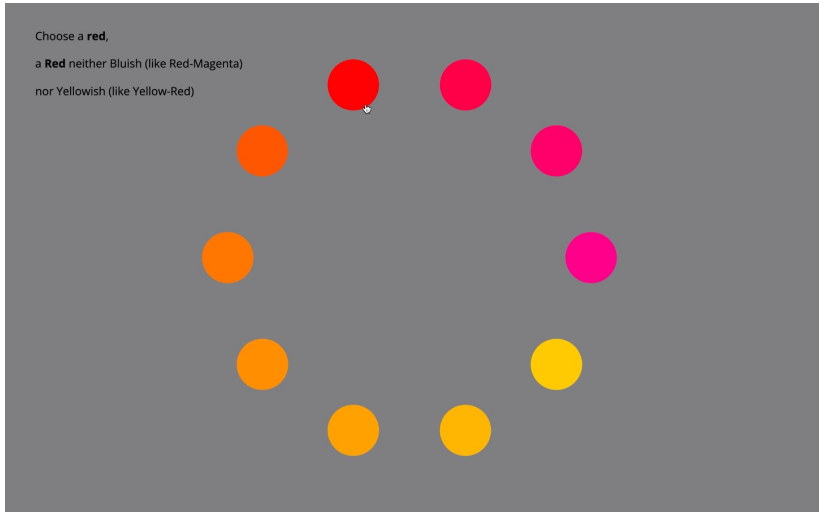
Grey scale preservation



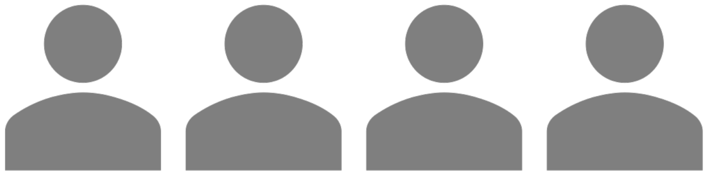
Hue selection (Second stage)

Calibration file



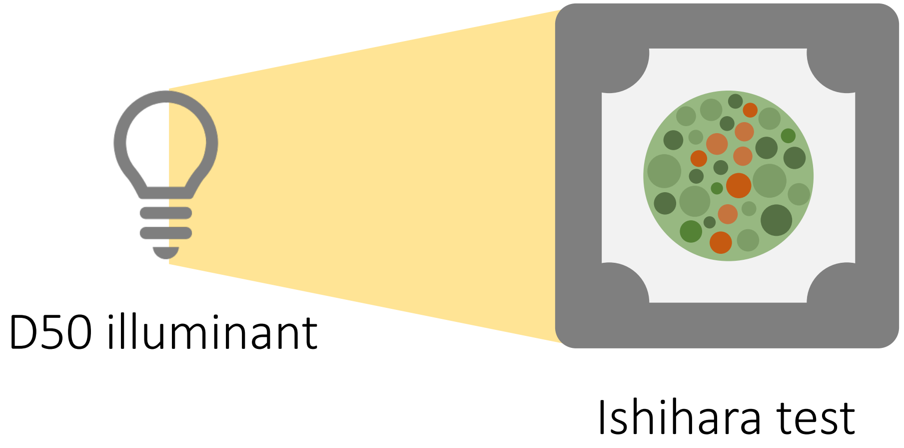


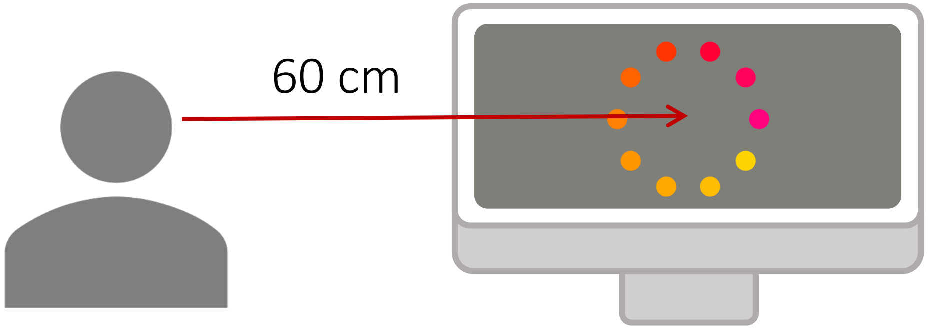
Experimental Methodology



- 13 participants
- 9 males and 3 females
- Mean age: 26 years old
- Age range: 21-51 years old

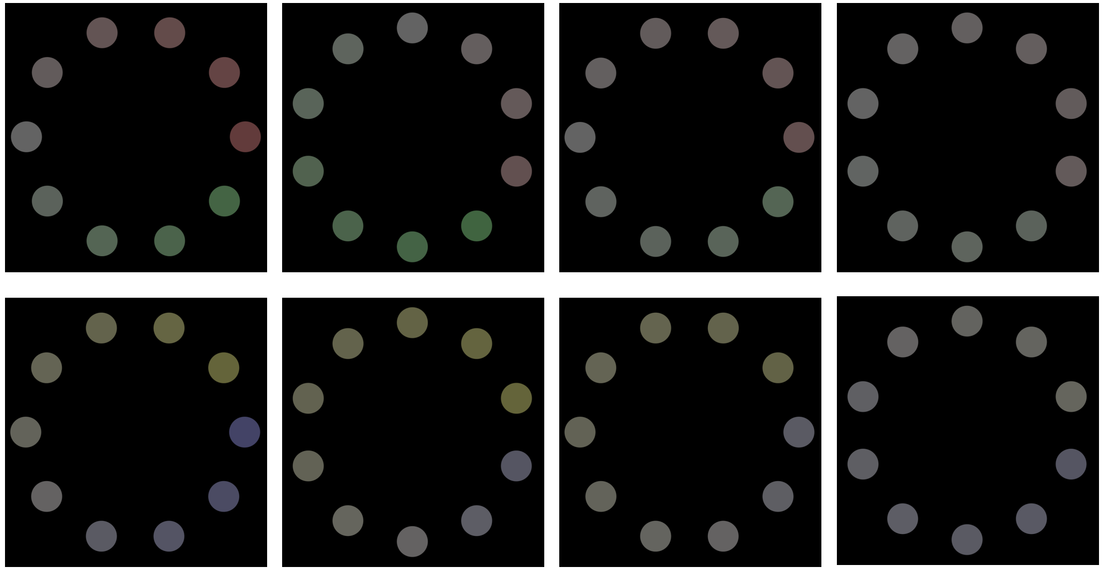
~15 minutes

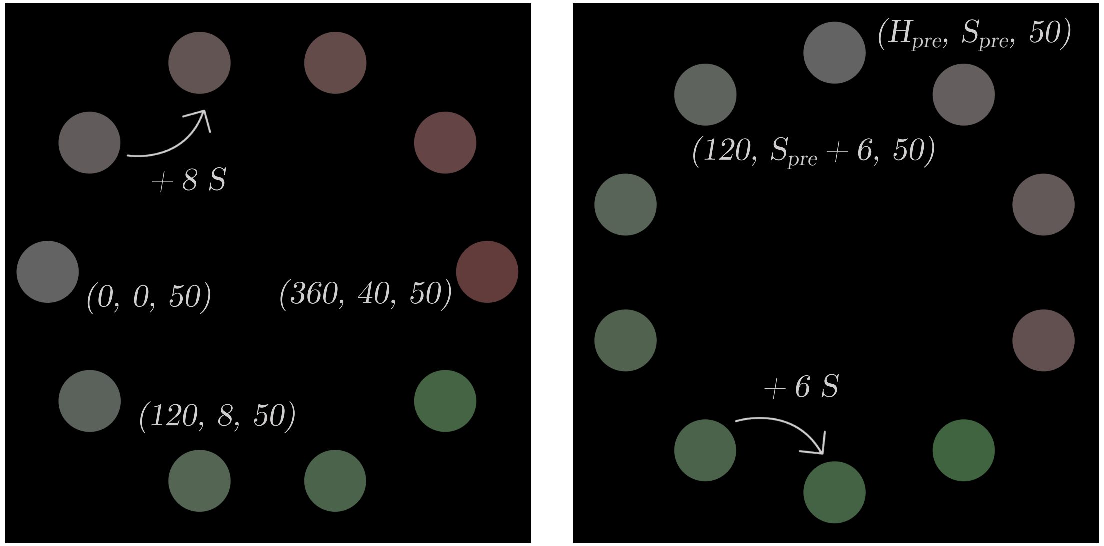




Neutral background stage

- **Achromatic background:**
  - R = G = B = 1 not necessarily correct for an uncalibrated device
  - Color appearance depends on the surrounding colors
- **Hue axes (HSV):**
  - Red–Green axis (0º - 120º)
  - Yellow-Blue axis (60º - 240º)
- **Saturation shift (HSV):**
  - Whithin a trial, from the theoretical grey increases in a clockwise and counter clockwise direction
  - Decreases between trials → "Zoom in"
- **Value (HSV):** constant





where H_{pre} is the previous selected Hue and S_{pre} is the previous selected Saturation in HSV color space.

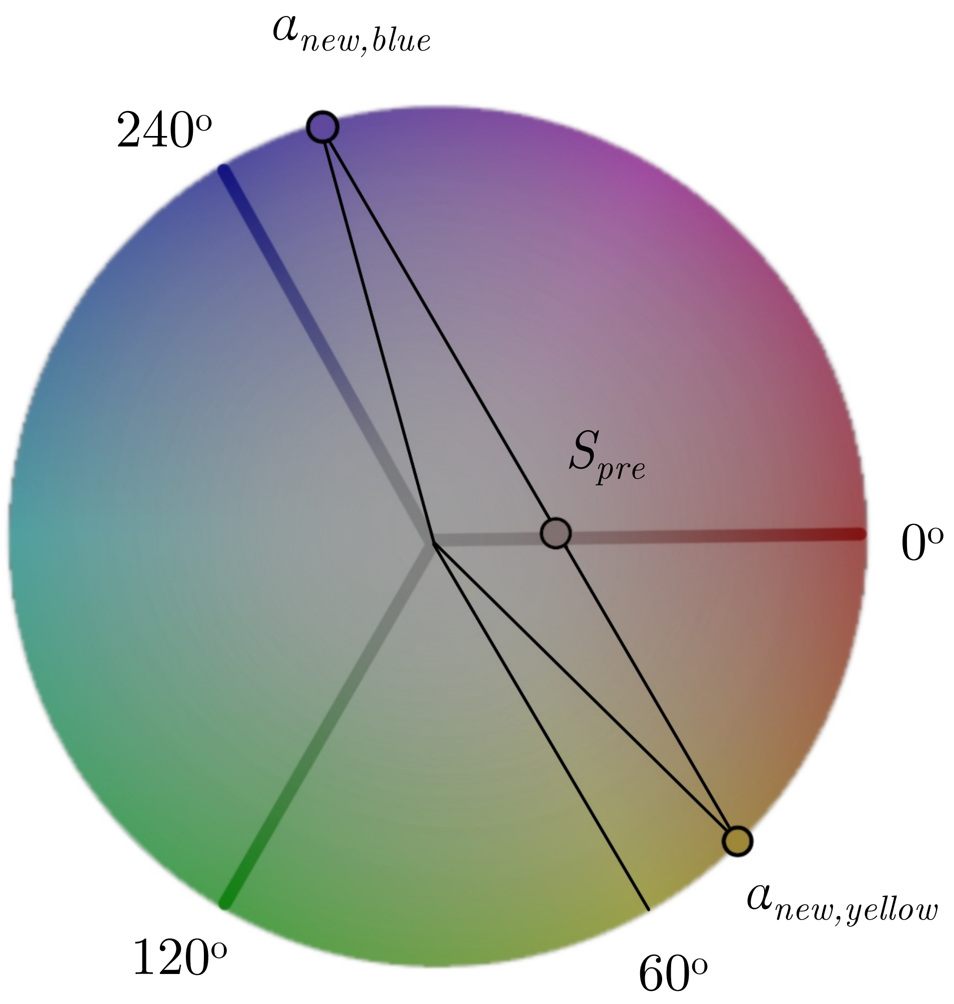
Neutral background stage

New hue angles calculation

$$\frac{S_{max}}{\sin 120^\circ} = \frac{S_{pre}}{\sin(60^\circ - \alpha_{new,yellow})},$$

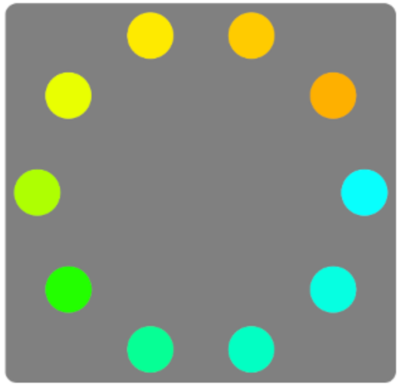
$$\alpha_{new,yellow} = 60^\circ - \arcsin\left(\frac{S_{pre}\sin 120^\circ}{S_{max}}\right),$$

$$\alpha_{new,blue} = 120^\circ - \alpha_{new,yellow}$$

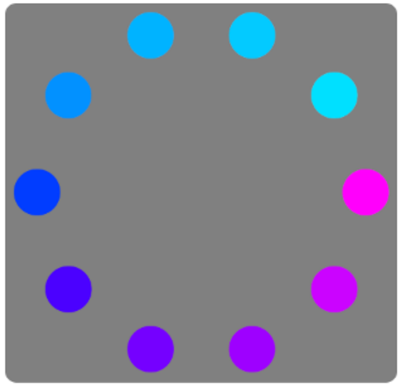


Hue selections stage

Red: neither Bluish (like Red-Magenta) nor Yellowish (like Yellow-Red)

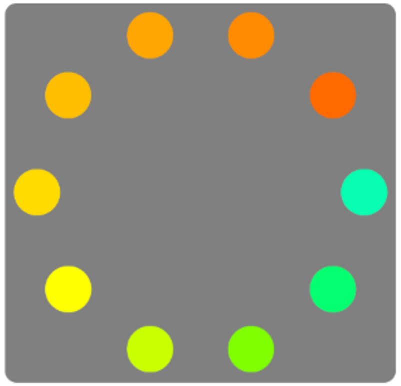


Green: neither Yellowish (like Green-Yellow) nor Bluish (like Cyan-Green)



Blue: neither Greenish (like Cyan-Green) nor Reddish (like Magenta-Blue)

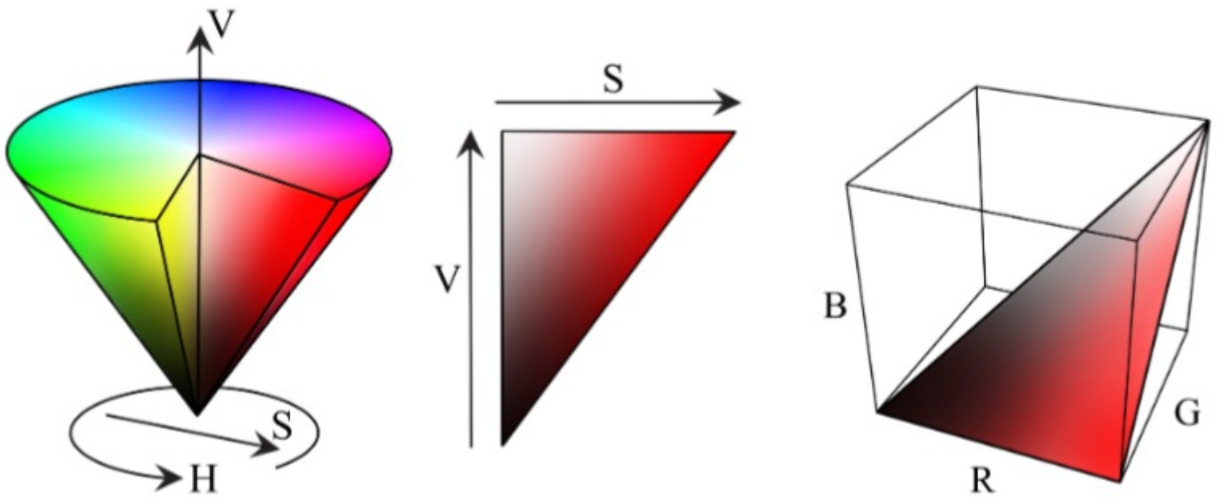
Orange: neither Reddish (like Red) nor Yellowish (like Yellow)

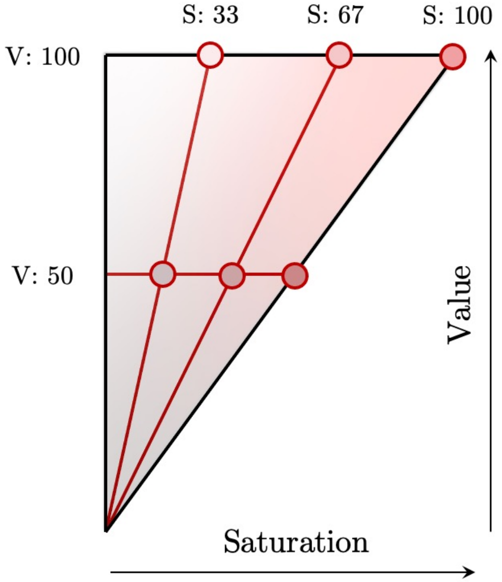


Yellow: neither Greenish (like Green-Yellow) nor Reddish (like Yellow-Red)

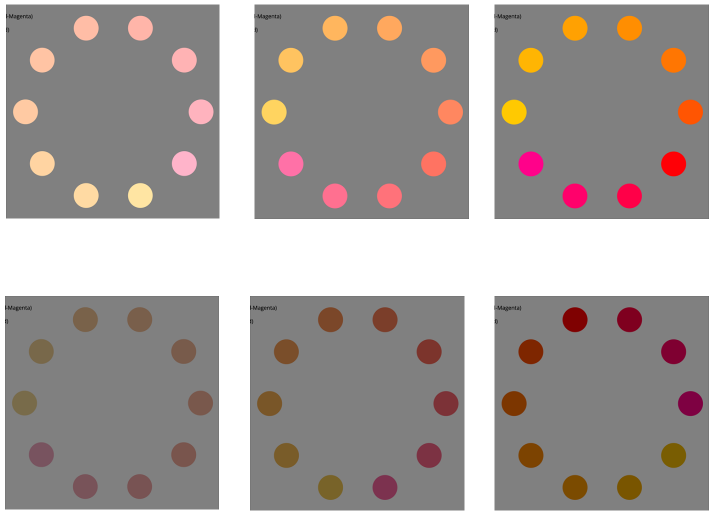
Hue selections stage

- Define the hue planes in a psychologically-defined three-dimensional color space
- HSV color space as reference:
  - Hue planes are contained in a cone
  - Saturation and Hue axes define a specific hue plane
- Hue selection trial:
  - Saturation and Value are constant
  - Hue changes
  - For different combinations of Saturation and Value levels → selected colors define the hue plane





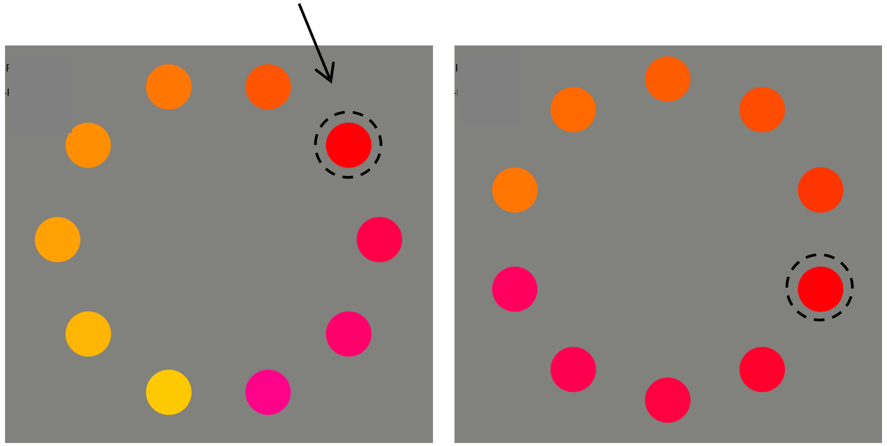
Saturation-Value combinations (trials)

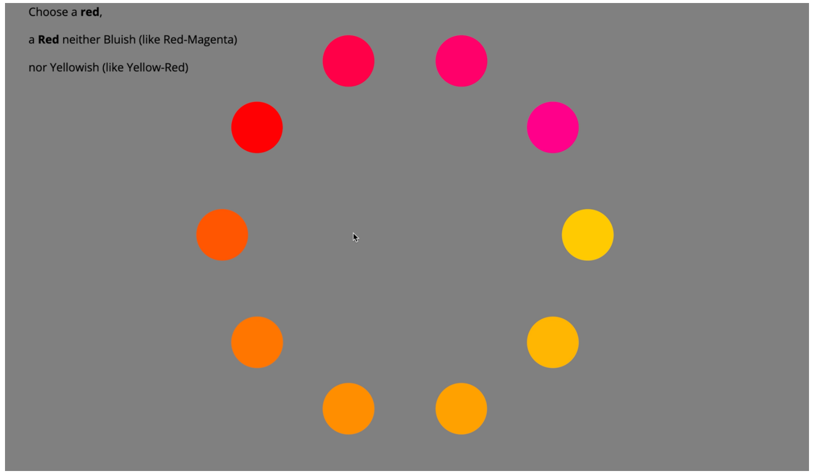


Hue selections stage

Selected patch

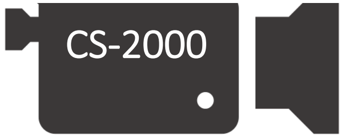
"Zoom in"



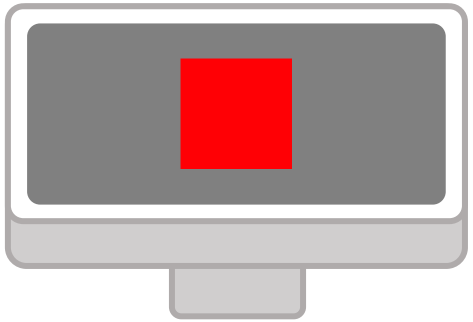


- After experiments:
  - Selected color coordinates saved in data file: construct profile
  - The patches were redisplayed and measured with the CS-2000 Spectroradiometer from Konica Minolta

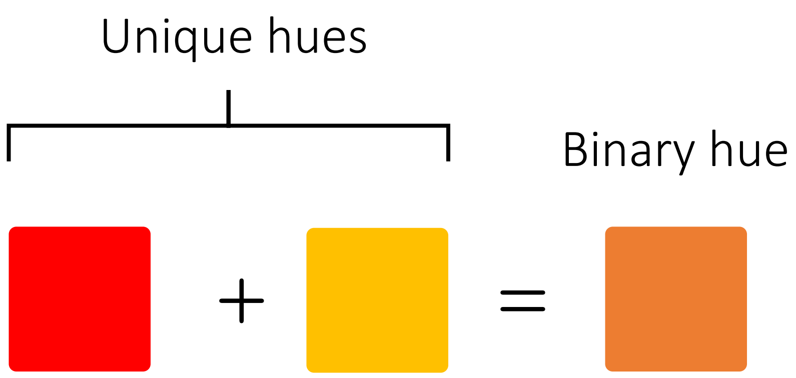
Spectroradiometer

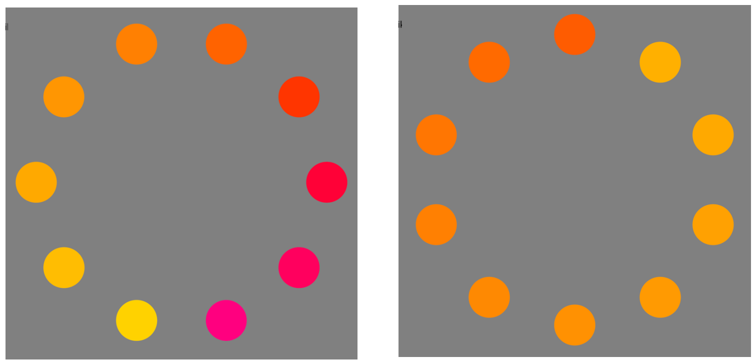


Redisplayed selected patch



Added binary hue





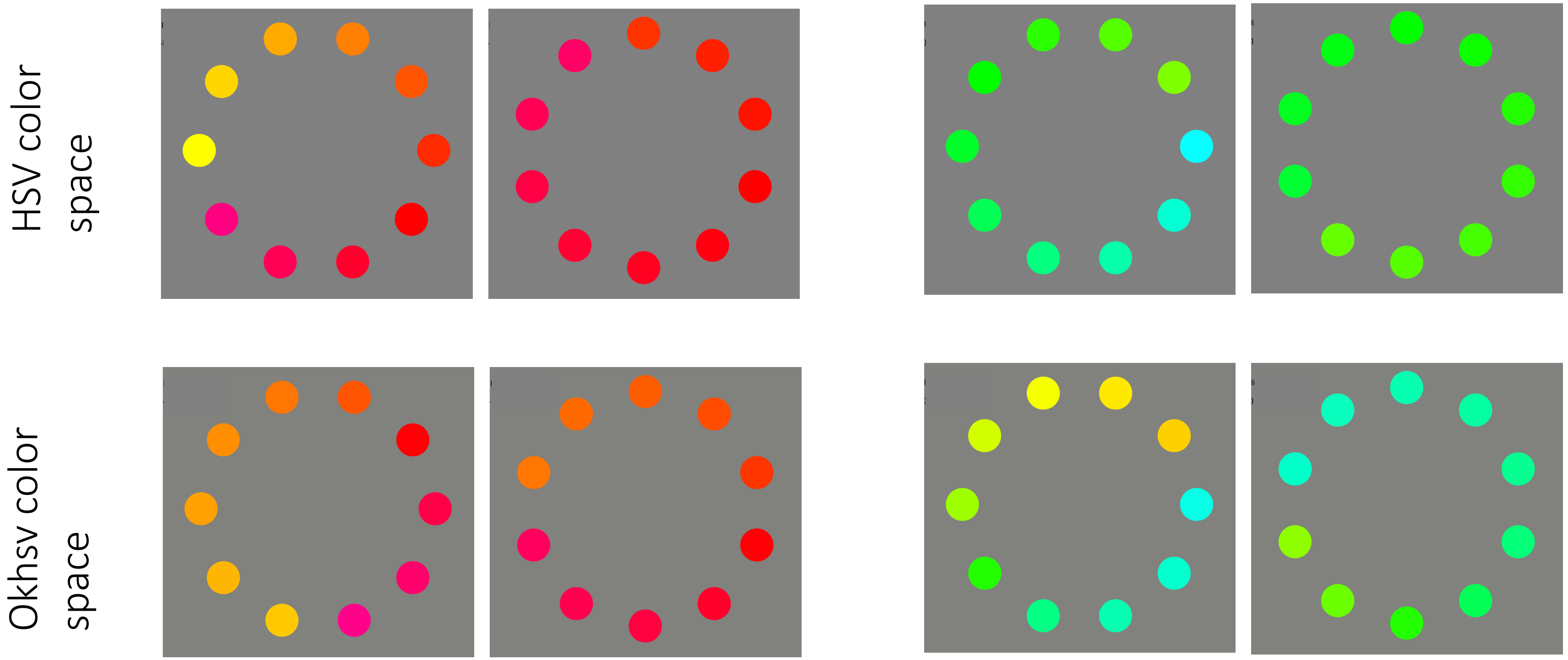
- **Binary hues:**
  - Mixture of unique hues
  - Unique hues and Binary hues are same in terms of phenomenological experience
  - A binary hue were implemented to compare binary and unique hues performance

- **Orange hue:**
  - To obtain an accurate calibration applicable to all users → search hues with the least inter- and intra-observer variability
  - One of the hues with lowest variance within and between observers is orange

Implemented Color Spaces

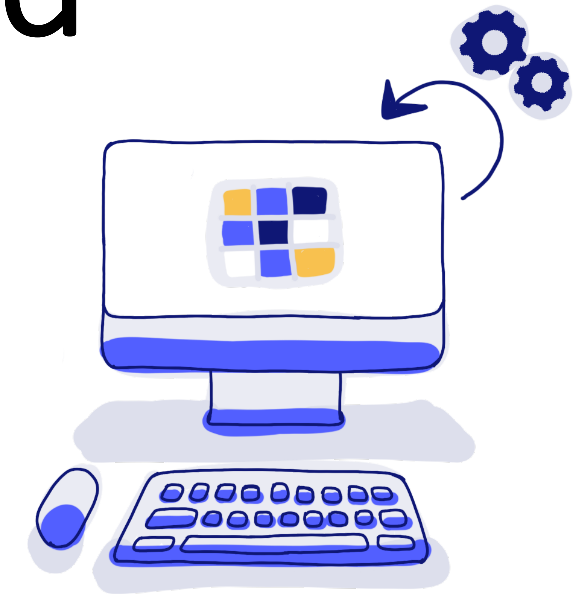
- **Neutral background stage:**
  - HSV is not supported by the standard web content development → Transformations between HSL and HSV color spaces to show the stimuli

- **Hue selections stage:** Okhsv color space *(Ottosson, 2021)*
  - Improves the homogeneity of the hue angle spacing between patches
  - Similar hue ranges for all hues

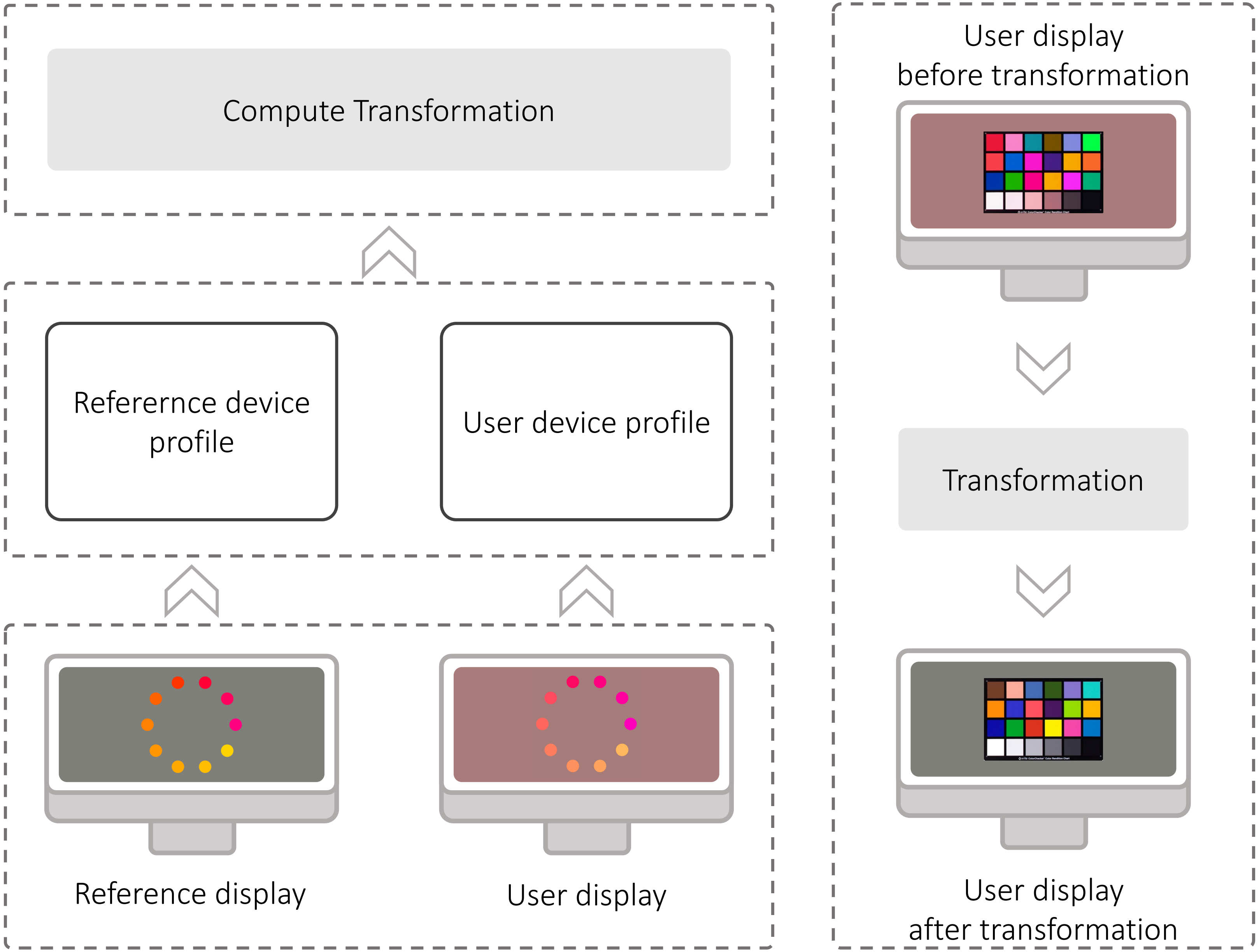


Calibration Method

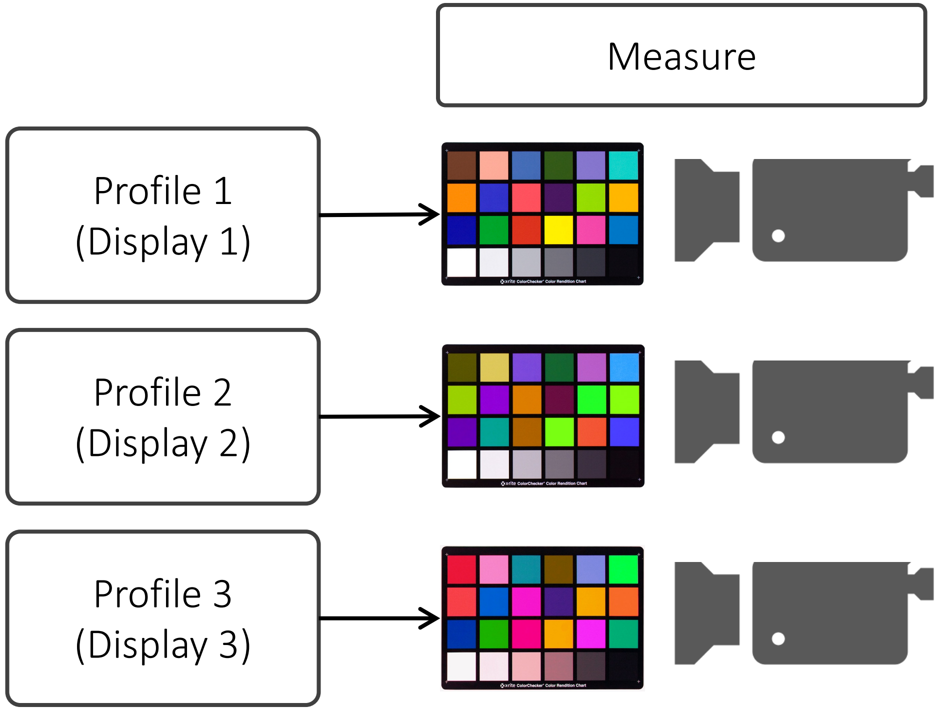
- *Calibration Process*
- *Calibration Methodology*
- *Display Characterization*
- *Display Profile*
- *Matrix-Based transformations*



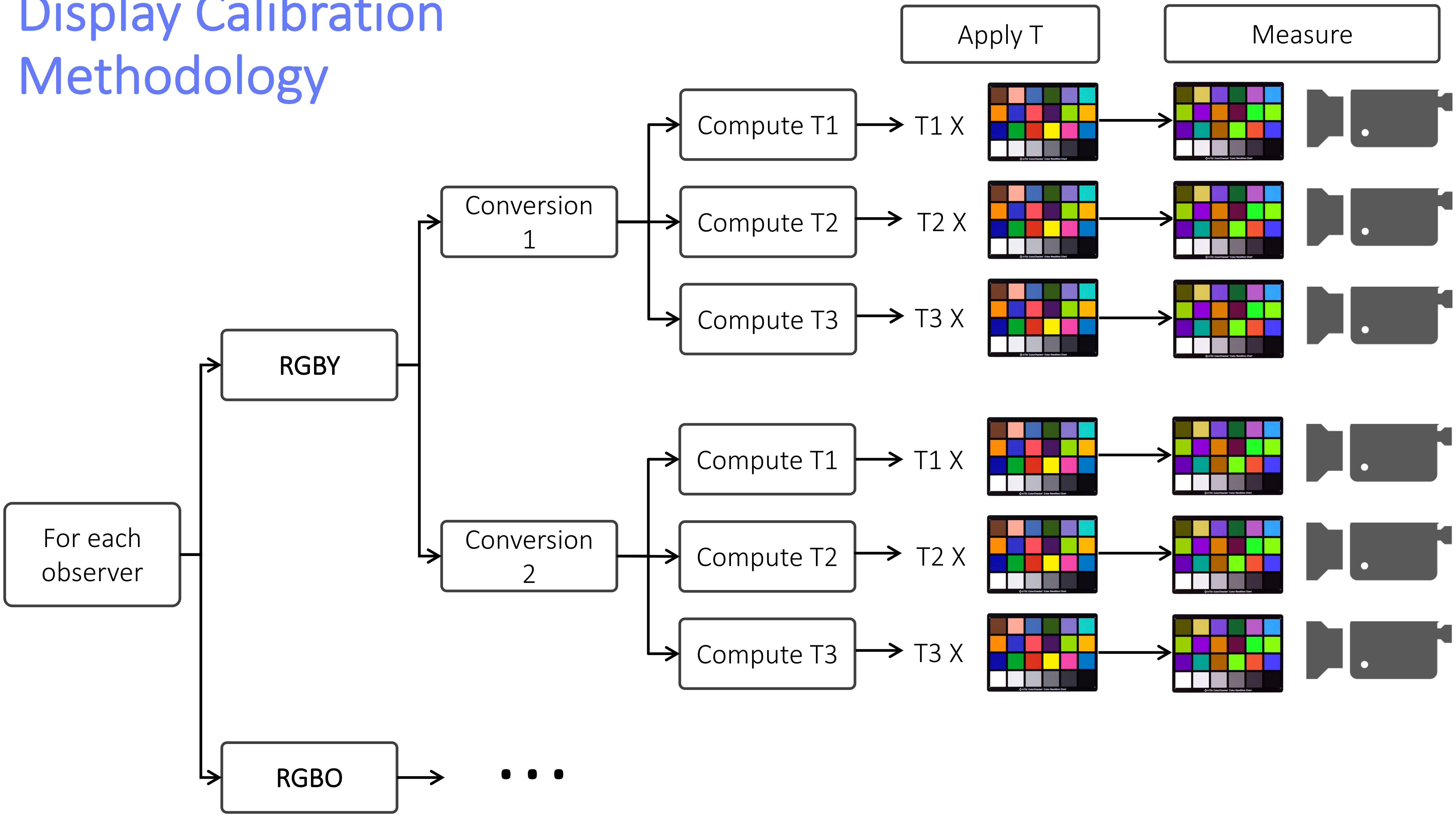
Display Calibration Process



Display Calibration Methodology



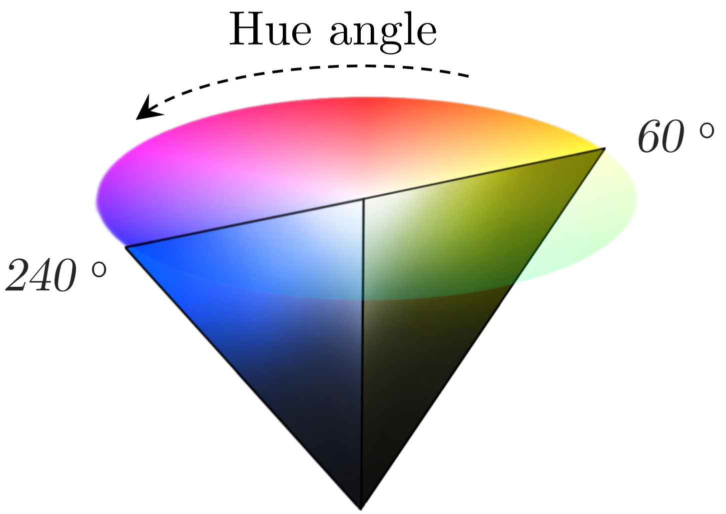
Display Calibration Methodology



Hue Combinations

- **Hue set 1** (four unique hues):
  - Includding Yellow hue: better estimation of yellow-blue plane
  - No new plane information added

- **Hue set 2** (binary hue added):
  - Orange hue plane is linearly unrelated to unique hue planes
  - Adds new plane information



Hue Set 1	*Hue Set 2*
RGBY	RGBO
Red	Red
Green	Green
Blue	Blue
Yellow	Orange

Designed Profiles

- Three profiles designed using sRGB specifications (standard color space on the web):
  - Hue shift
  - White point shift
- Same physical properties but different color behaviour
- Motivations:
  - To control the color behaviour of the display
  - Analysis purely focused on colorimetric changes → isolate from other factors such as physical properties, gamma value, or brightness

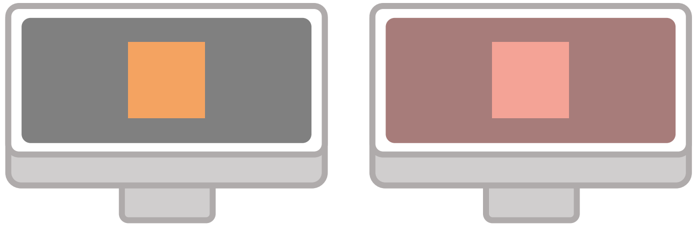
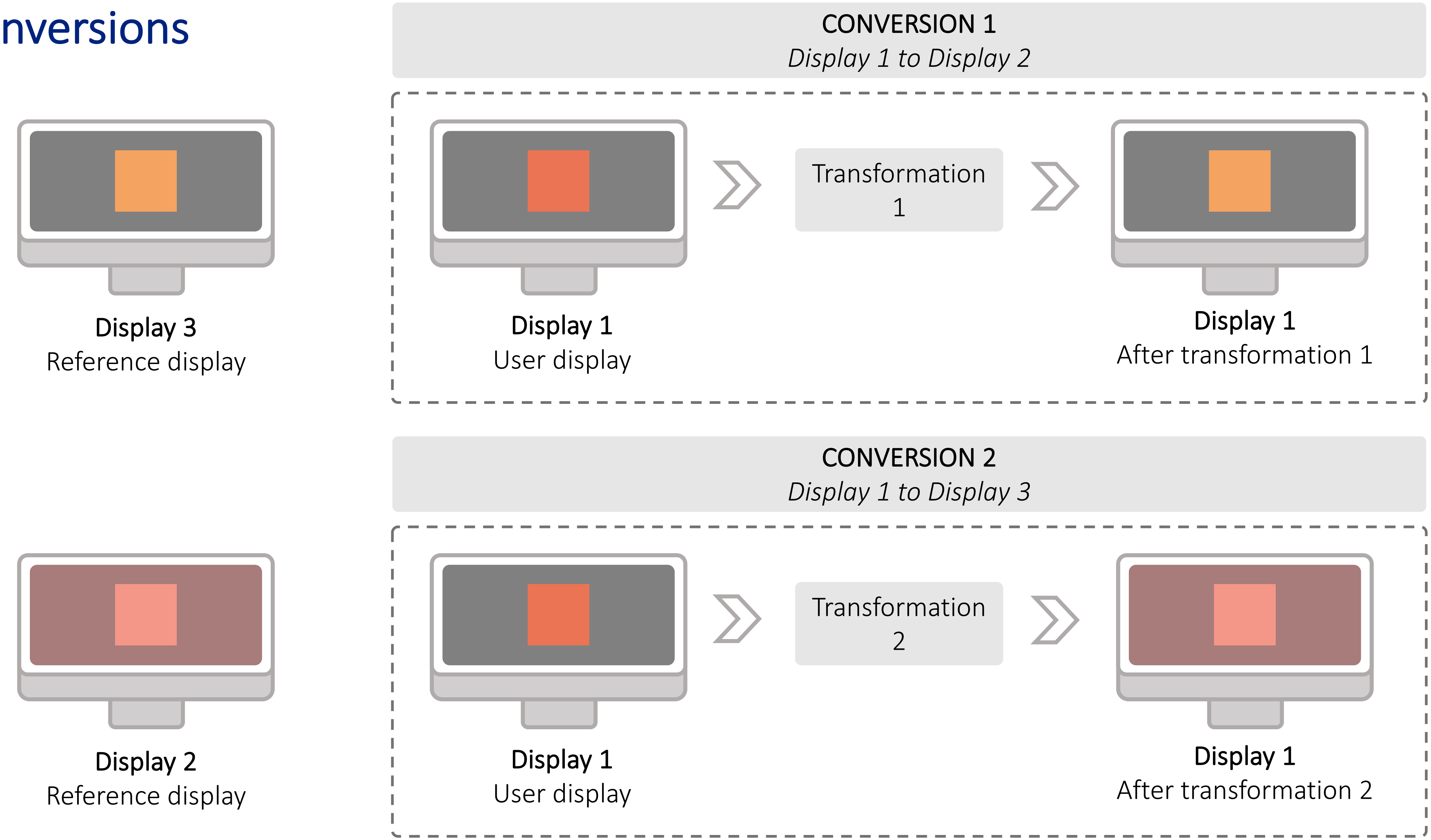


Table 4.1: Designed profiles white point and hue specifications.

	White point (RGB percentage)	Hues shift (degrees)
Profile 1	(100, 90.45, 73.16)–sRGB	0
Profile 2	(100, 90.45, 73.16)–sRGB	+ 16
Profile 3	(100, 48.28, 30.07)	– 16

Conversions



Display Characterization

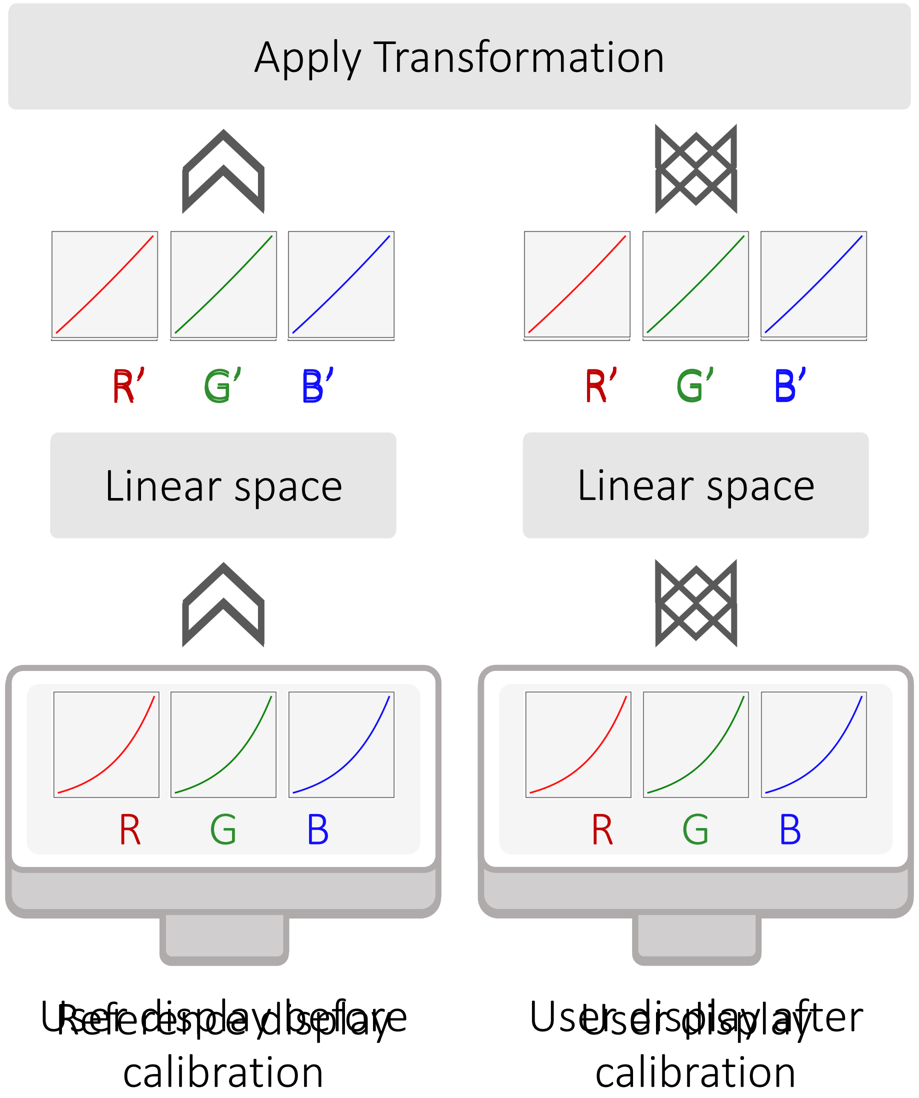
- Digital RGB values (device-dependent) do not represent the display color appearance
- Characterization → mathematical relationship between input voltage and the light intensity output

Signal-to-Light intensity function

$$\underbrace{\text{Light-intensity output}}_{\text{Device-independent}} = (gain \cdot \underbrace{\text{input voltage}}_{\text{Device-dependent}} + offset)^{\gamma},$$

- Knowing the function parameters:

Device-dependent color space → Device-independent color space



Display Characterization

- Calibration method aims to eliminate the need for an external reference
- Two approaches:
  - Visual approaches: several techniques to estimate the gamma *(γ)*, offset *(f)* and gain *(g)* *(To et al., 2013) (Ban and Yamamoto, 2013) (Parraga et al., 2014) (Hainich and Bimber, 2016)*
  - Gamma, offset and gain estimation *(Wuerger, 2008)*:
    - Calculate Normal plane
    - RGB Points
    - Light-intensity relationship

    Standard Minimization
- In our experiment we calibrated the display with our designed profiles, thus we directly applied the reduced light-intensity equation

Signal-to-Light intensity function

$$\text{Light-intensity output} = (gain \cdot \text{input voltage} + offset)^{\gamma},$$

$$\text{Light-intensity output} = \text{input voltage}^{\gamma}.$$

Hue planes equations

$$a_{\bar{R}}(g \cdot R + f)^{\gamma} + b_{\bar{R}}(g \cdot G + f)^{\gamma} + c_{\bar{R}}(g \cdot B + f)^{\gamma} + d_{\bar{R}} = 0,$$

$$a_{\bar{G}}(g \cdot R + f)^{\gamma} + b_{\bar{G}}(g \cdot G + f)^{\gamma} + c_{\bar{G}}(g \cdot B + f)^{\gamma} + d_{\bar{G}} = 0,$$

$$a_{\bar{B}}(g \cdot R + f)^{\gamma} + b_{\bar{B}}(g \cdot G + f)^{\gamma} + c_{\bar{B}}(g \cdot B + f)^{\gamma} + d_{\bar{B}} = 0.$$

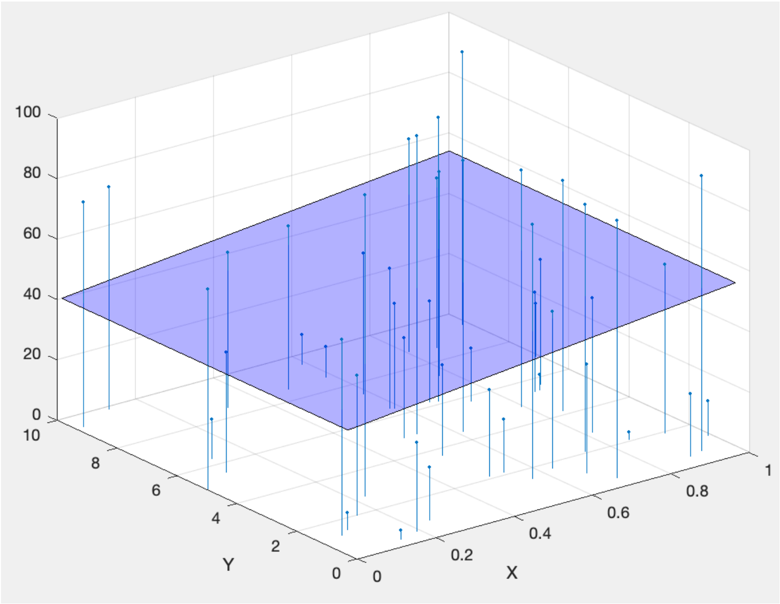
Display Profile

Hue judgment data from a specific display

Display Profile

- Hue RGB coordinates
- Signal-to-Light intensity function
- Normal vectors in linear RGB space

- RGB coordinattes are fitted in a plane in the linear RGB space
- Minimization of the sum of the quadratic distances between the 3D points and the predicted plane
- The Normal defines the plane orientation in the 3D space



Matrix-Based transformations

Point-to-Point transformation

- Purpose: linear user-RGB → linear reference-RGB
- Unconstrained nonlinear optimization in the linear RGB space
  - Objective function → RMSE between predicted linear user-RGB after the transformation and the linear reference-RGB
- Advantages: not limited by a number of coordinates to define the plane equation of a single hue
  - Less assessments
  - Wide variety of hues

Predicted linear user-RGB after transformation

$$\begin{bmatrix} r^{lin} \\ g^{lin} \\ b^{lin} \end{bmatrix}^T_{pre,user} = \begin{bmatrix} r^{lin} \\ g^{lin} \\ b^{lin} \end{bmatrix}^T_{user} \cdot \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix}$$

Root-Mean-Square Error

$$RMSE = \sqrt{\frac{1}{n} \Sigma_{i=1}^{n} (x_i - \hat{x}_i)^2}$$

Point-to-Plane transformation

- *(Karatzas and Wuerger, 2007)*
- Purpose: linear reference-RGB → correspondent linear user-RGB hue planes
- Constrained nonlinear optimization:
  - Objective function: RMSE of the distance between the transformed linear reference-RGB and the linear user-RGB planes
  - Constraints:
    - Elements in each row of the transformation matrix is set to be 1
    - The highest saturation is preserved after transformation

Minimizes the distance between reference-RGB points and user-RGB plane

$$\begin{bmatrix} r_h^{lin} & g_h^{lin} & b_h^{lin} \end{bmatrix}_{ref} \cdot \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \cdot \begin{bmatrix} \alpha_h^{lin} \\ \beta_h^{lin} \\ \gamma_h^{lin} \end{bmatrix}_{user} = 0$$

Constraints

$$t_{11} + t_{12} + t_{13} = 1; t_{21} + t_{22} + t_{23} = 1; t_{31} + t_{32} + t_{33} = 1.$$

$$\begin{bmatrix} r^{lin} \\ g^{lin} \\ b^{lin} \end{bmatrix}_{ref}^{T} = \begin{bmatrix} r^{lin} \\ g^{lin} \\ b^{lin} \end{bmatrix}_{ref}^{T} \cdot \begin{bmatrix} t_{11} & 0 & 0 \\ 0 & t_{22} & 0 \\ 0 & 0 & t_{33} \end{bmatrix}$$

Point-to-Plane Grey scale preservation

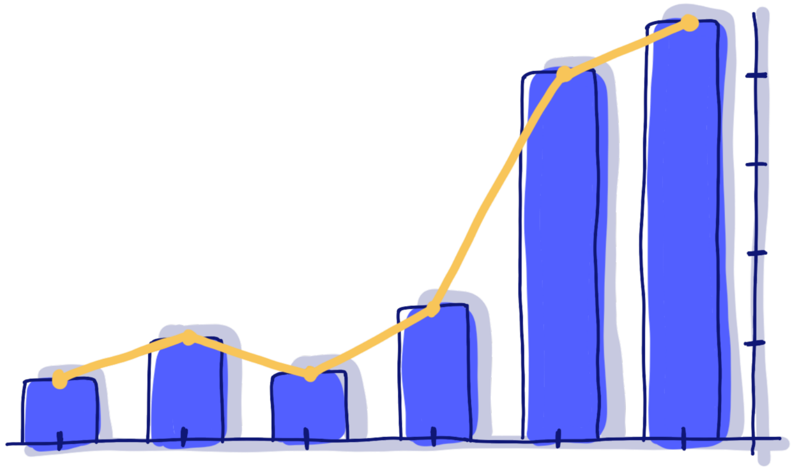
- Motivation:
  - Color perception relative to a white reference
  - White chromaticities impact in appearance of surrounding colors
- Purpose: linear reference-RGB → correspondent linear user-RGB hue planes preserving grey scale
- Additional constraint:
  - From neutral grey → Preservation after the matrix-based transformation

Additional constraint

$$\begin{bmatrix} r^{lin} \\ g^{lin} \\ b^{lin} \end{bmatrix}^T_{ref,grey} = \begin{bmatrix} r^{lin} \\ g^{lin} \\ b^{lin} \end{bmatrix}^T_{user,grey} \cdot \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix}$$

Results and Discussion

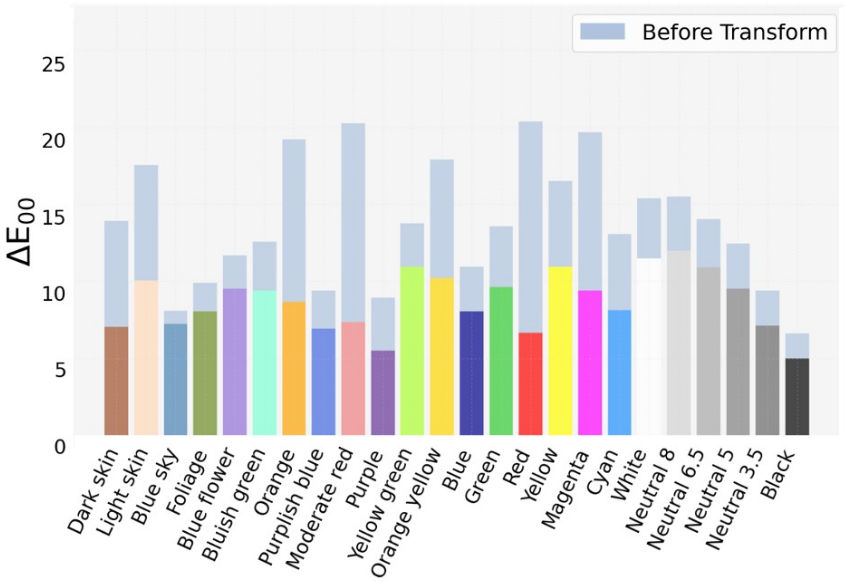
- *From Display 1 to Display 2*
- *From Display 1 to Display 3*
- *Hue combinations*



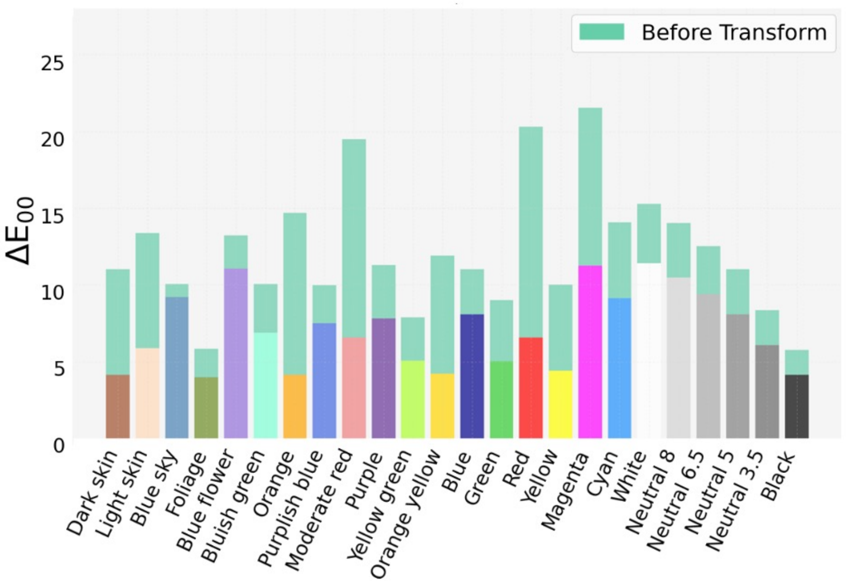
From Display 1 to Display 2

Color Difference per ColorChecker patch

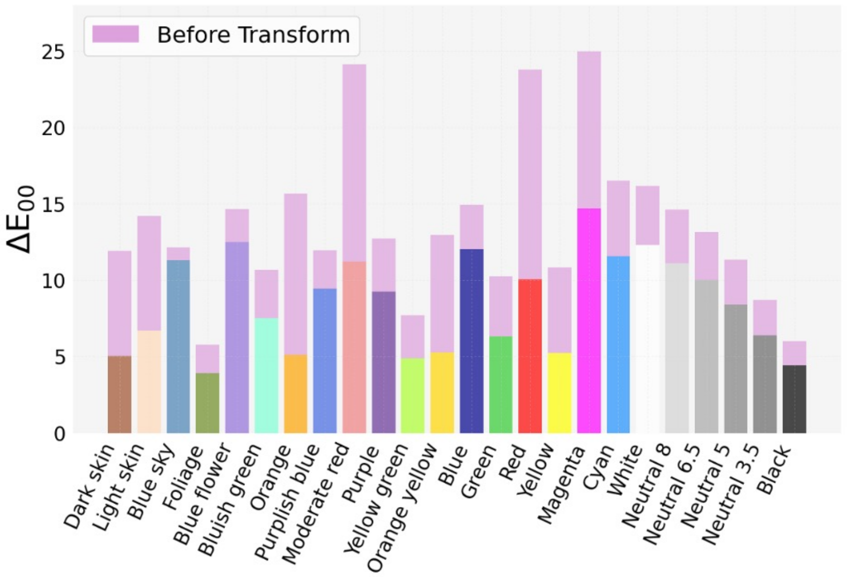
Point-to-Point Transformation



Point-to-Plane Transformation



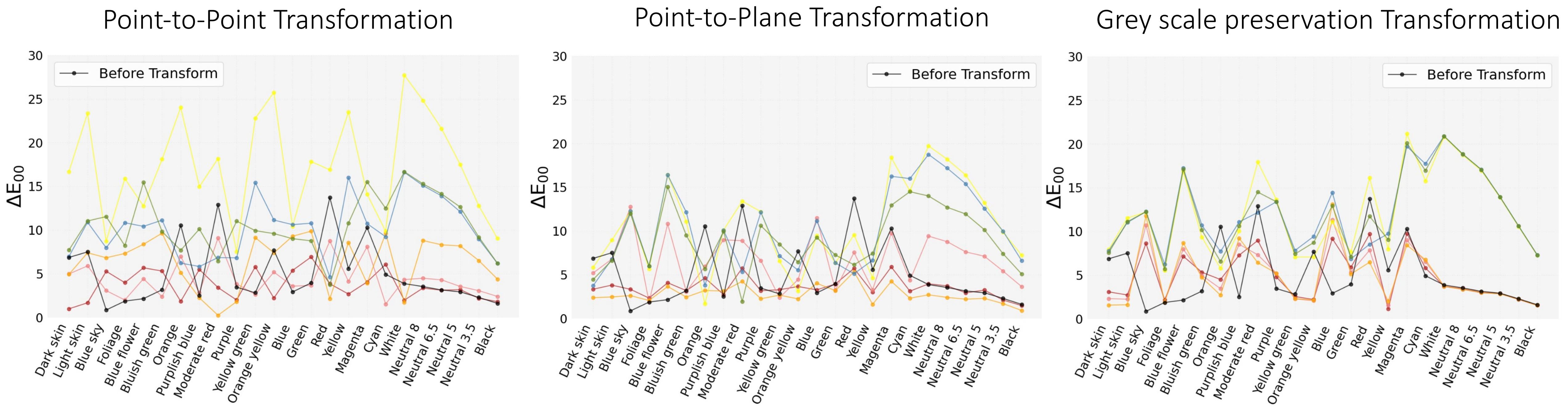
Grey scale preservation Transformation



(ΔE_{00})	T Point-to-Point		T Point-to-Plane		T Grey scale	
Conversions	Mean	STD	Mean	STD	Mean	STD
D1 to D2	8.7353	5.1550	7.1126	3.4728	8.5330	3.7914
D1 to D3	20.9393	4.4262	19.04475	5.5264	18.3841	5.1555

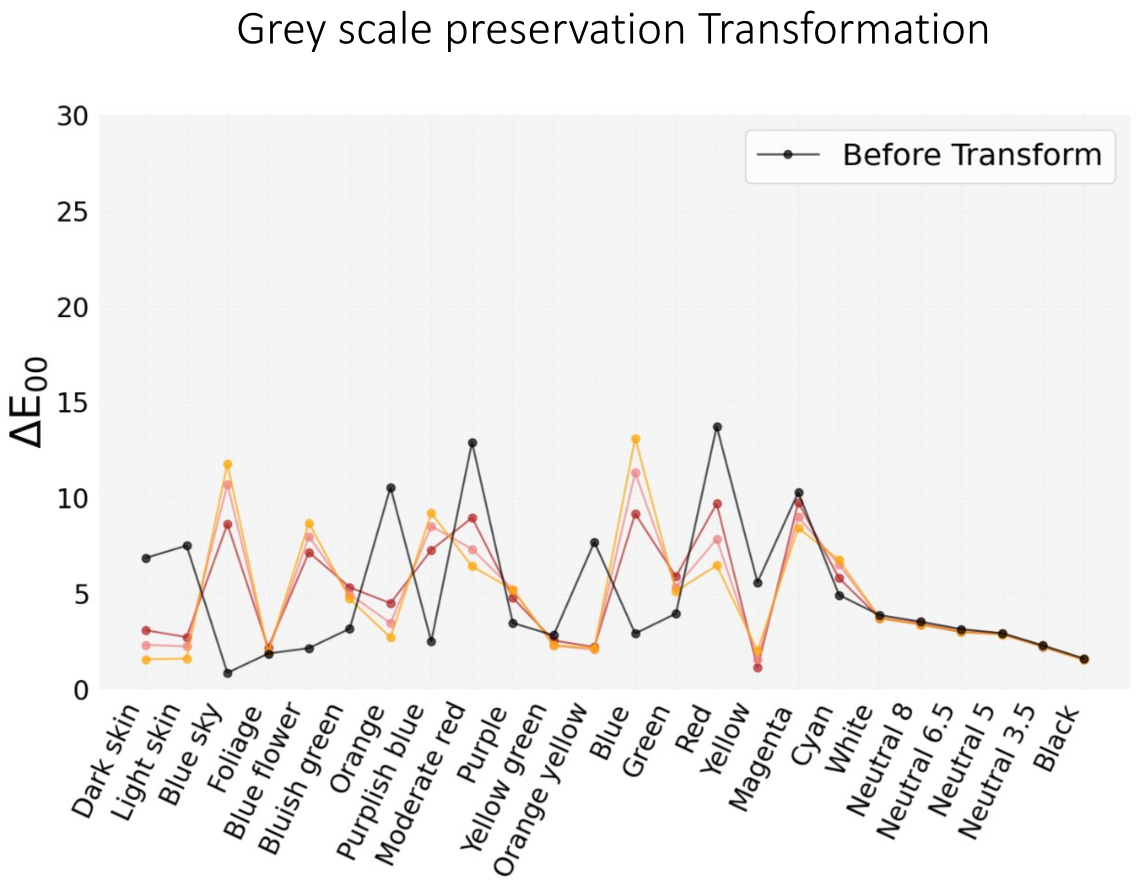
From Display 1 to Display 2

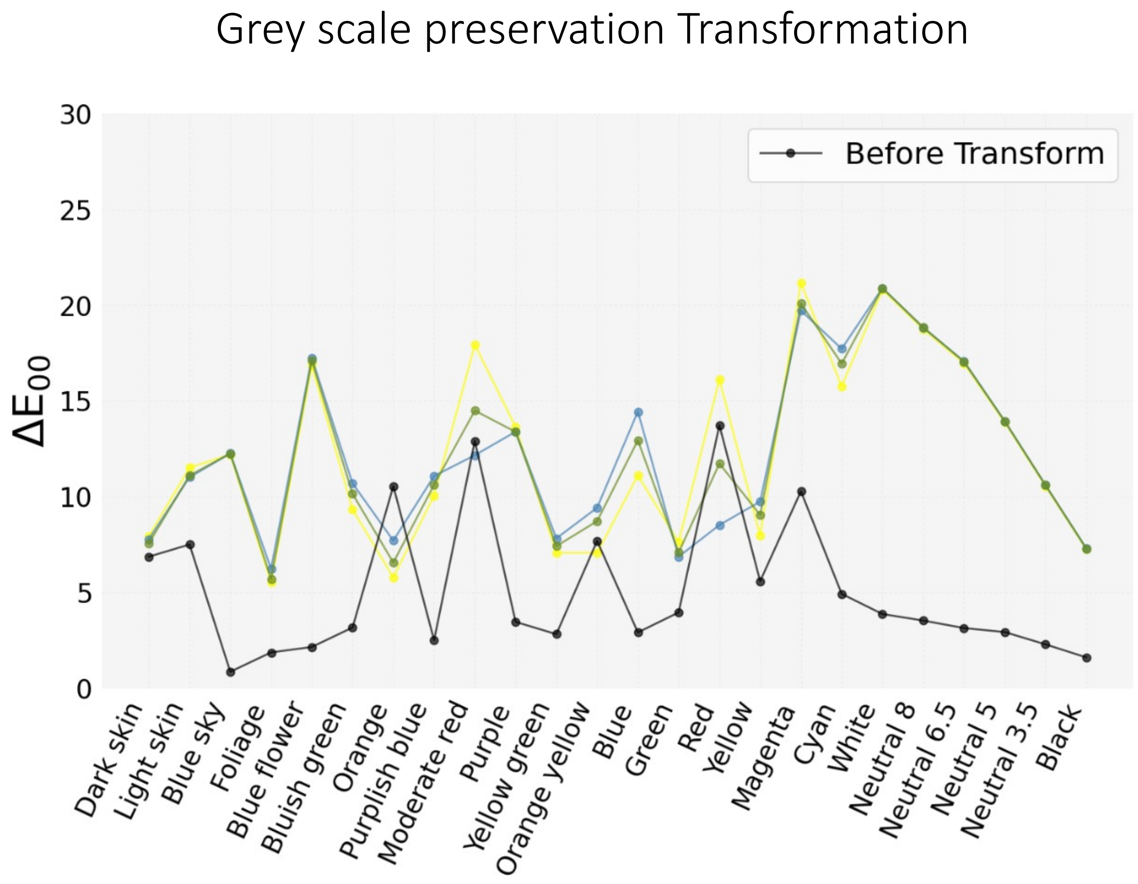
Color Difference per Observer



From Display 1 to Display 2

Color Difference per Observer

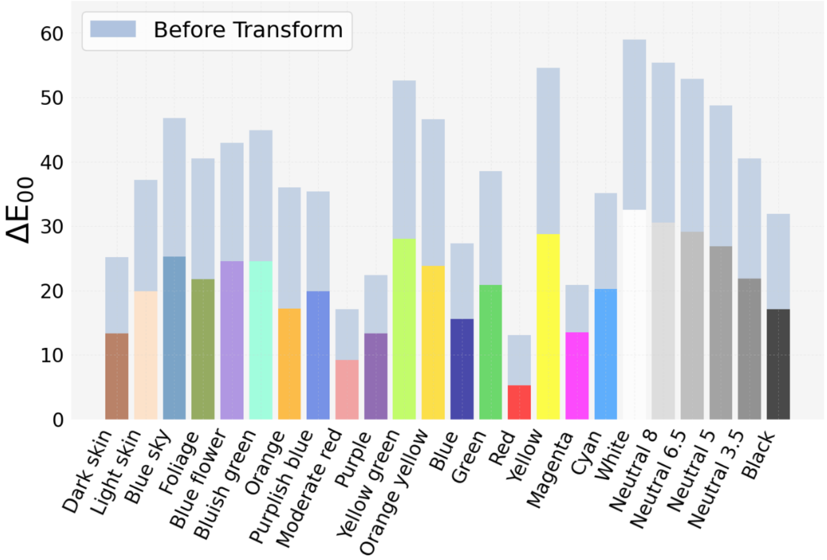




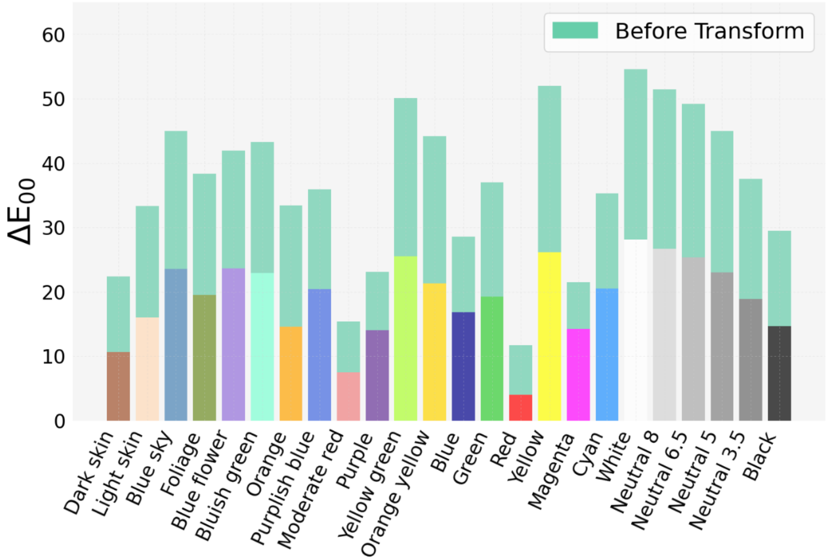
From Display 1 to Display 3

Color Difference per ColorChecker patch

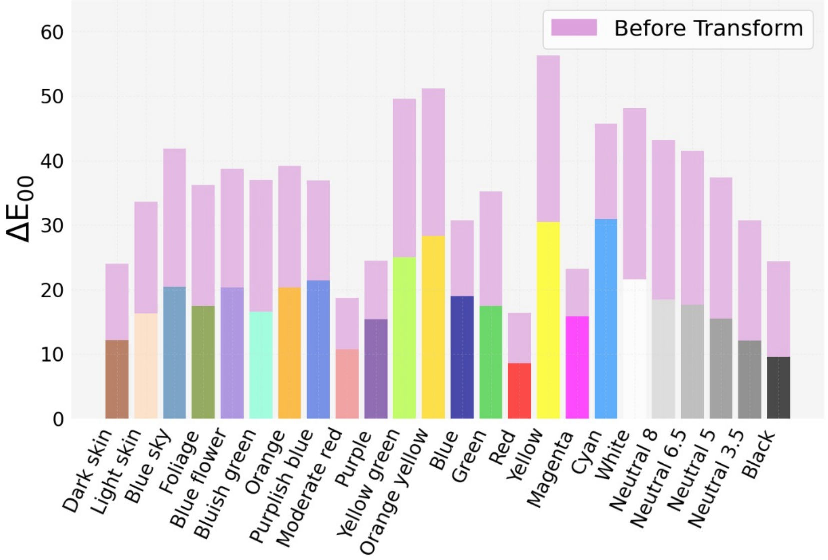
Point-to-Point Transformation



Point-to-Plane Transformation



Grey scale preservation Transformation

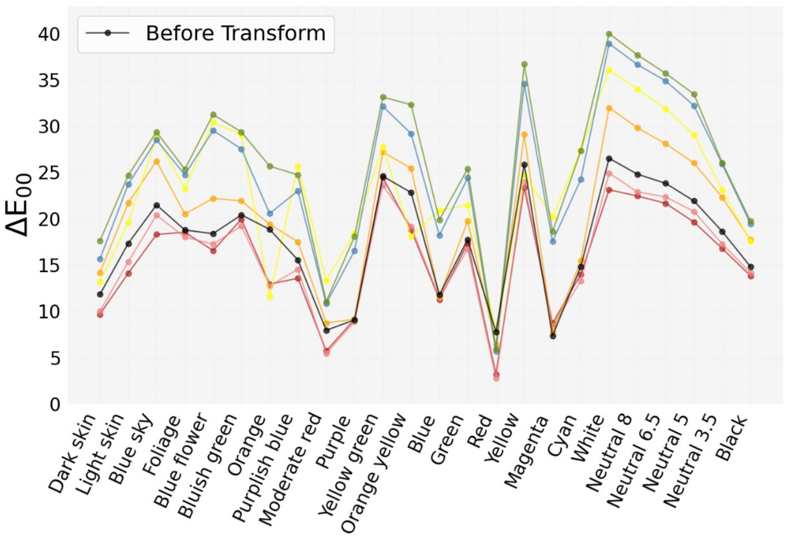


(ΔE_{00})	T Point-to-Point		T Point-to-Plane		T Grey scale	
Conversions	Mean	STD	Mean	STD	Mean	STD
D1 to D2	8.7353	5.1550	7.1126	3.4728	8.5330	3.7914
D1 to D3	20.9393	4.4262	19.04475	5.5264	18.3841	5.1555

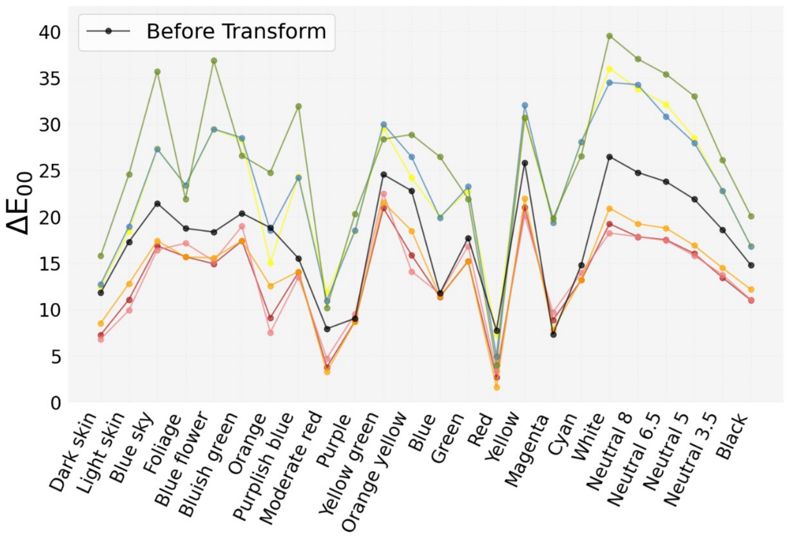
From Display 1 to Display 3

Color Difference per Observer

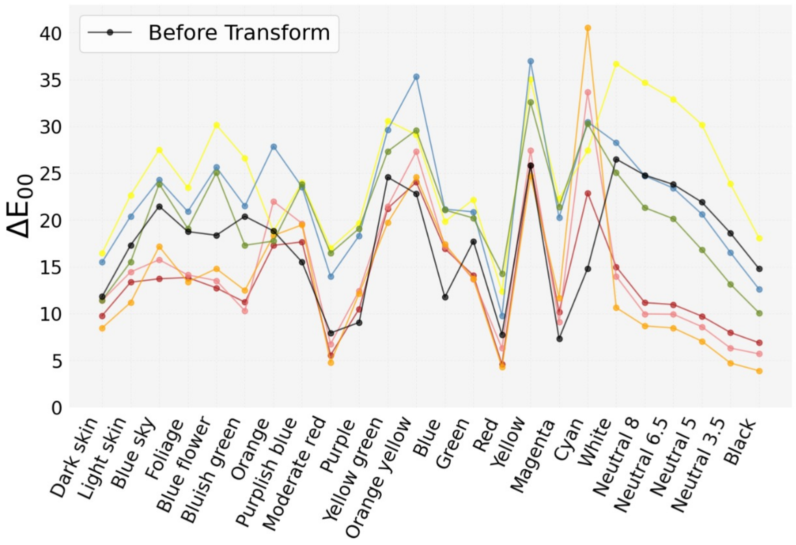
Point-to-Point Transformation



Point-to-Plane Transformation



Grey scale preservation Transformation

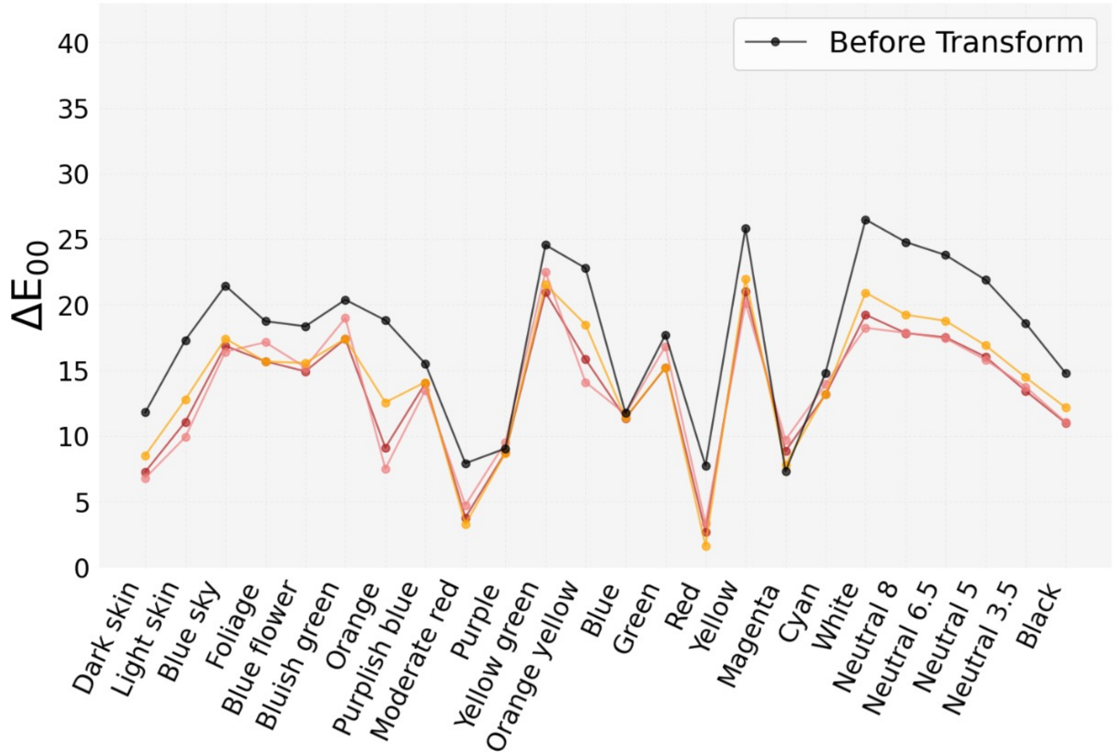


From Display 1 to Display 3

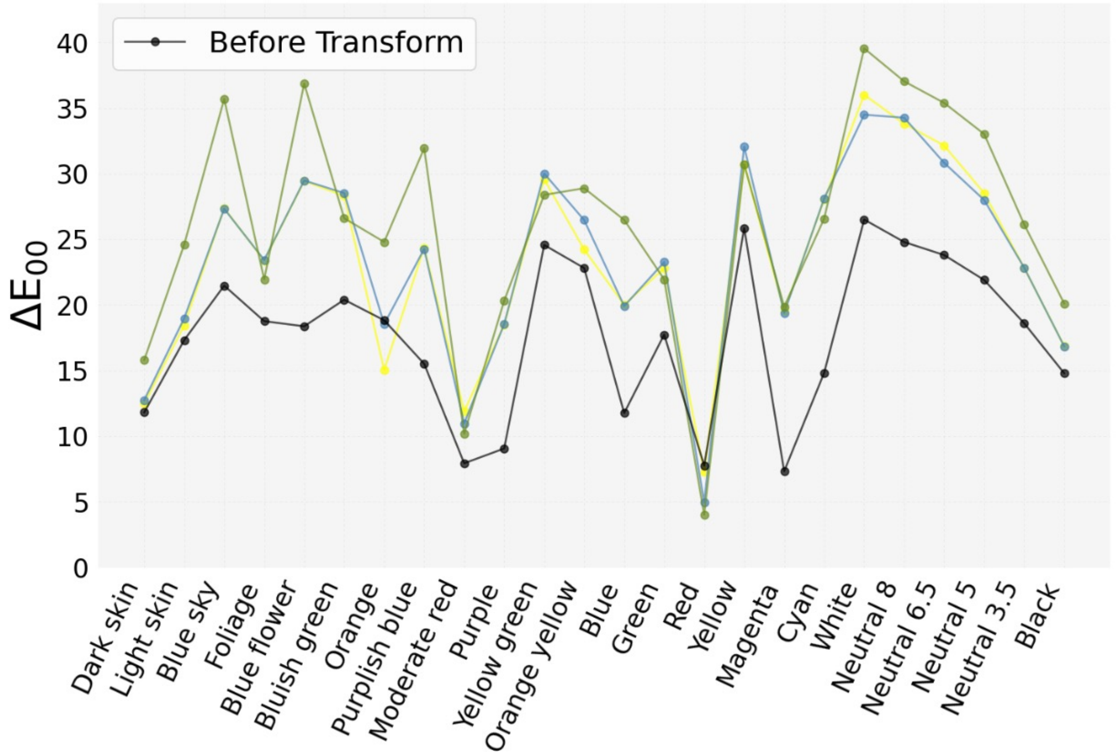
Color Difference per Observer

Point-to-Plane Transformation

First group of observers



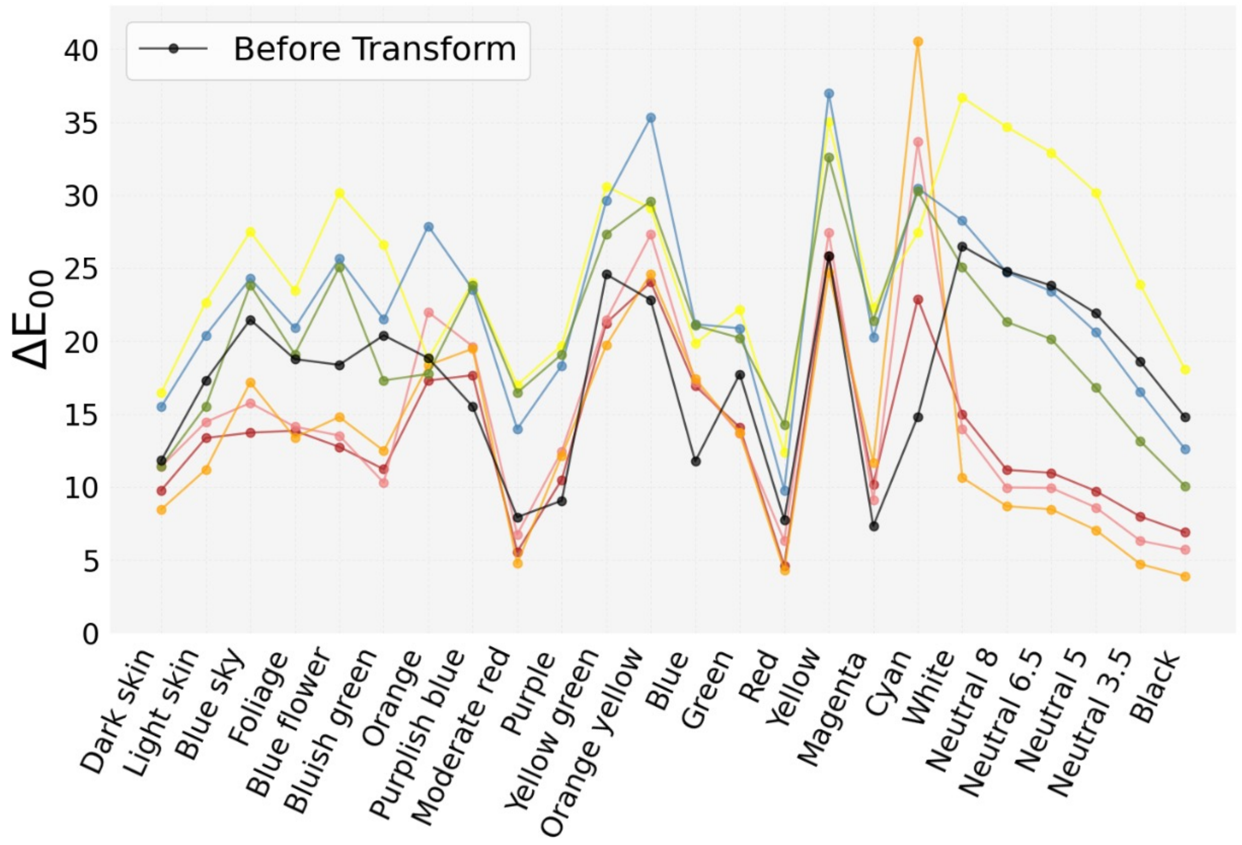
Second group of observers



From Display 1 to Display 3

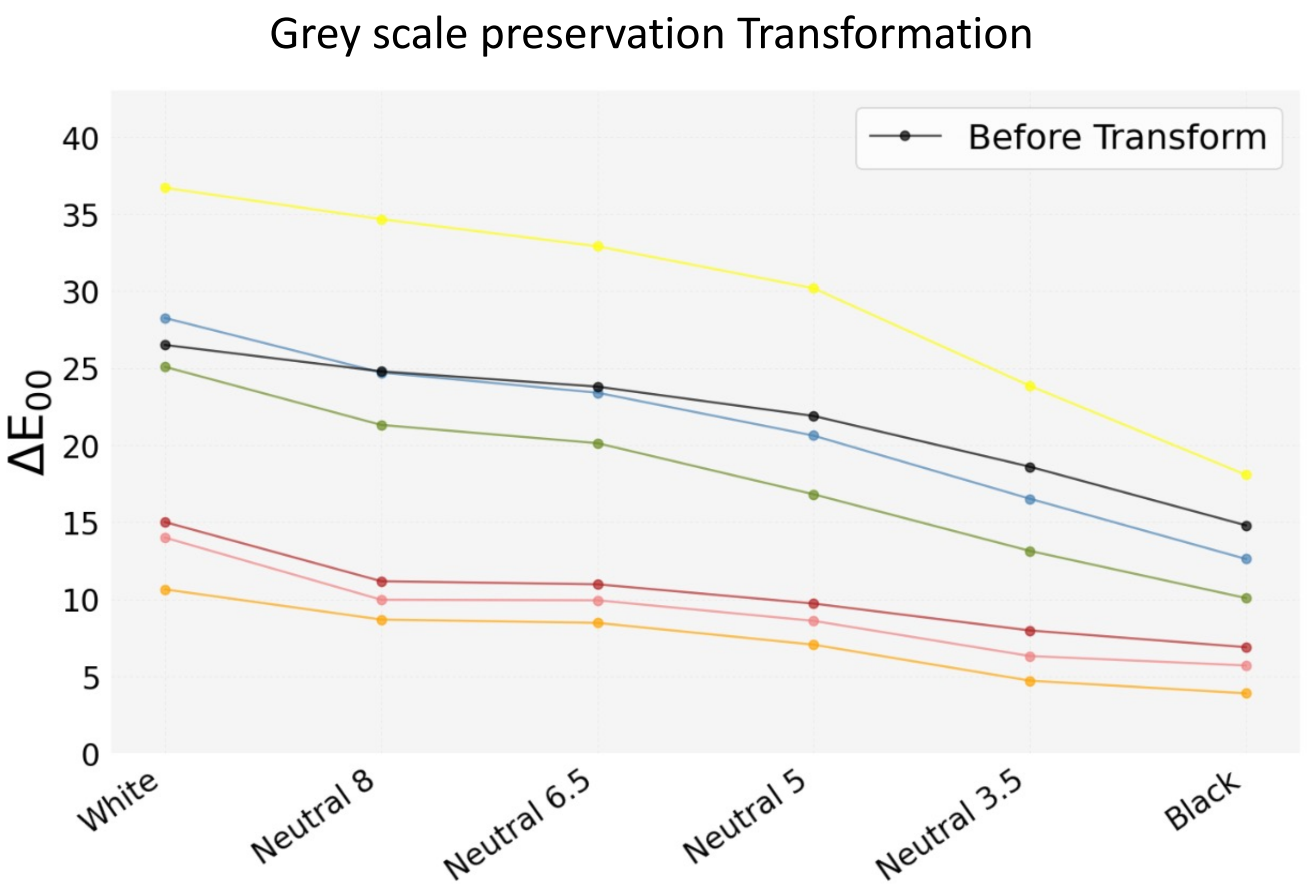
Color Difference per Observer

Grey scale preservation Transformation

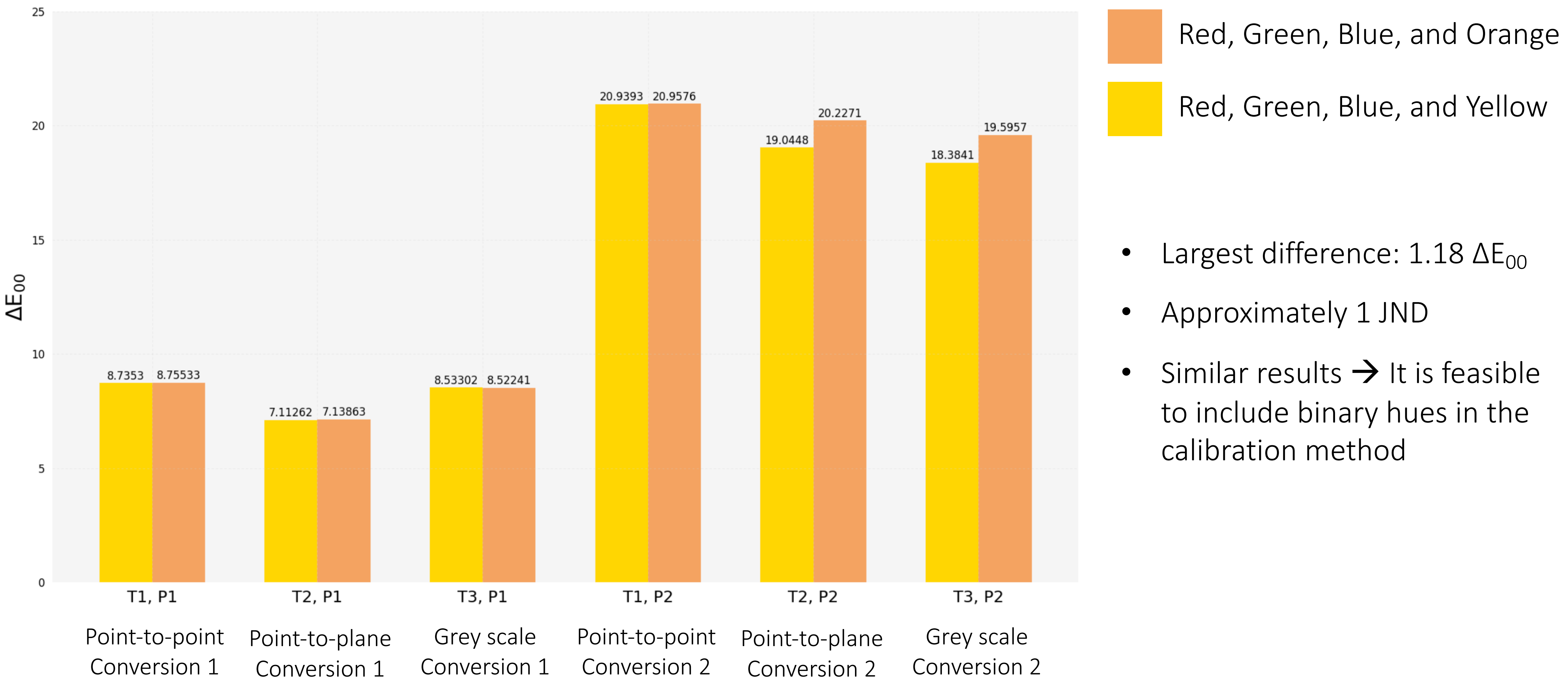


From Display 1 to Display 3

Color Difference per Observer



Hue Combinations



- Largest difference: 1.18 ΔE_{00}
- Approximately 1 JND
- Similar results → It is feasible to include binary hues in the calibration method

Conclusions

- *Summary & Contributions*
- *Future Work*

Summary & Contributions

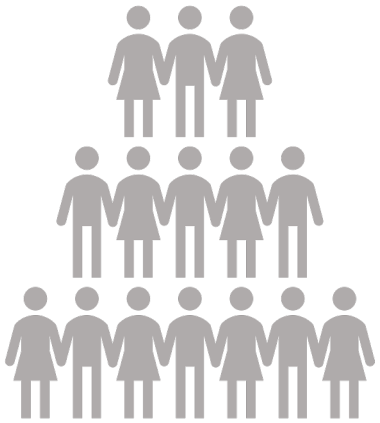
- A GUI was designed:
  - JavaScript:
    - Available for every device
    - It can be run online
  - Two rotations were introduced:
    - Prevent successive contrast
    - To cover all screen locations around the annulus
  - Color space improvement (Okhsv):
    - Homogeneity of the hue angle spacing between patches
    - Similar hue ranges for all hues
- Psychophysical experiments were conducted:
  - 3 Simulated displays
  - 13 Observers
- Matrix-Based Transformations were computed:
  - Point-to-Point
  - Point-to-Plane:
    - We provide for first time color difference results of the calibration performance applied to different observers
  - Greyscale Preservation
- Two hue combinations were implemented:
  - Results show the introduction of a binary hue is feasible
  - Advantages:
    - Reduce inter- and intra-observer variability
    - New plane information added
- Color difference data is provided:
  - Spectroradiometer

Summary & Contributions

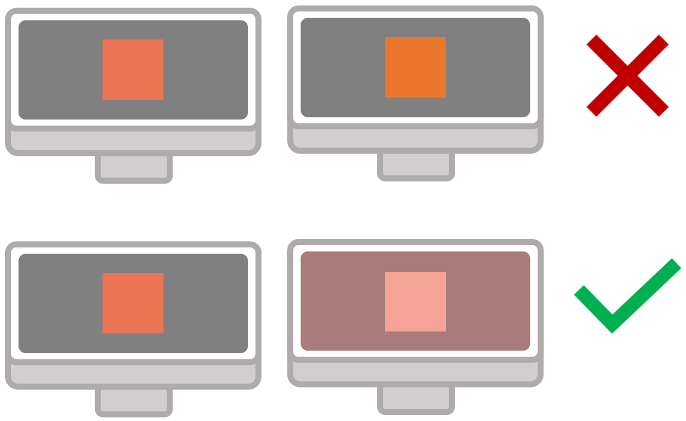
	Results	Advantages
Point-to-Point Transformation	Satisfactory results considering: • No constraints applied • The averaged color difference is approximately 1 JND	• Less number of assessments • Include more number of hues
Greyscale preservation Transformation	• Achieves greyscale preservation • Improves the results consistency for displays with small color differences	• Improvement in color match: given the importance of the grey scale

Is the Calibration method based on unique hues a reliable approach?

- Our results:



  - Rely too much on the observer
  - Not applicable to every observer
  - Previous color science knowledge could have a significant impact on the results



  - Small hue shift → Bad performance
  - Big hue shift → Better performance

- Study:
  - Trade off between observer variability and calibration performance
  - Large number of observers from different background
  - Process adjustments: best hue combinations

Future Works

Study different **hue combinations** including more binary hues

Psychophysical experiments to test the transformations applied in **real images**

Study how the **time** taking to select a hue affects the results

Apply the calibration method in an **uncontrolled environment**. Online experiments

Thank you for listening!

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Hue Combinations

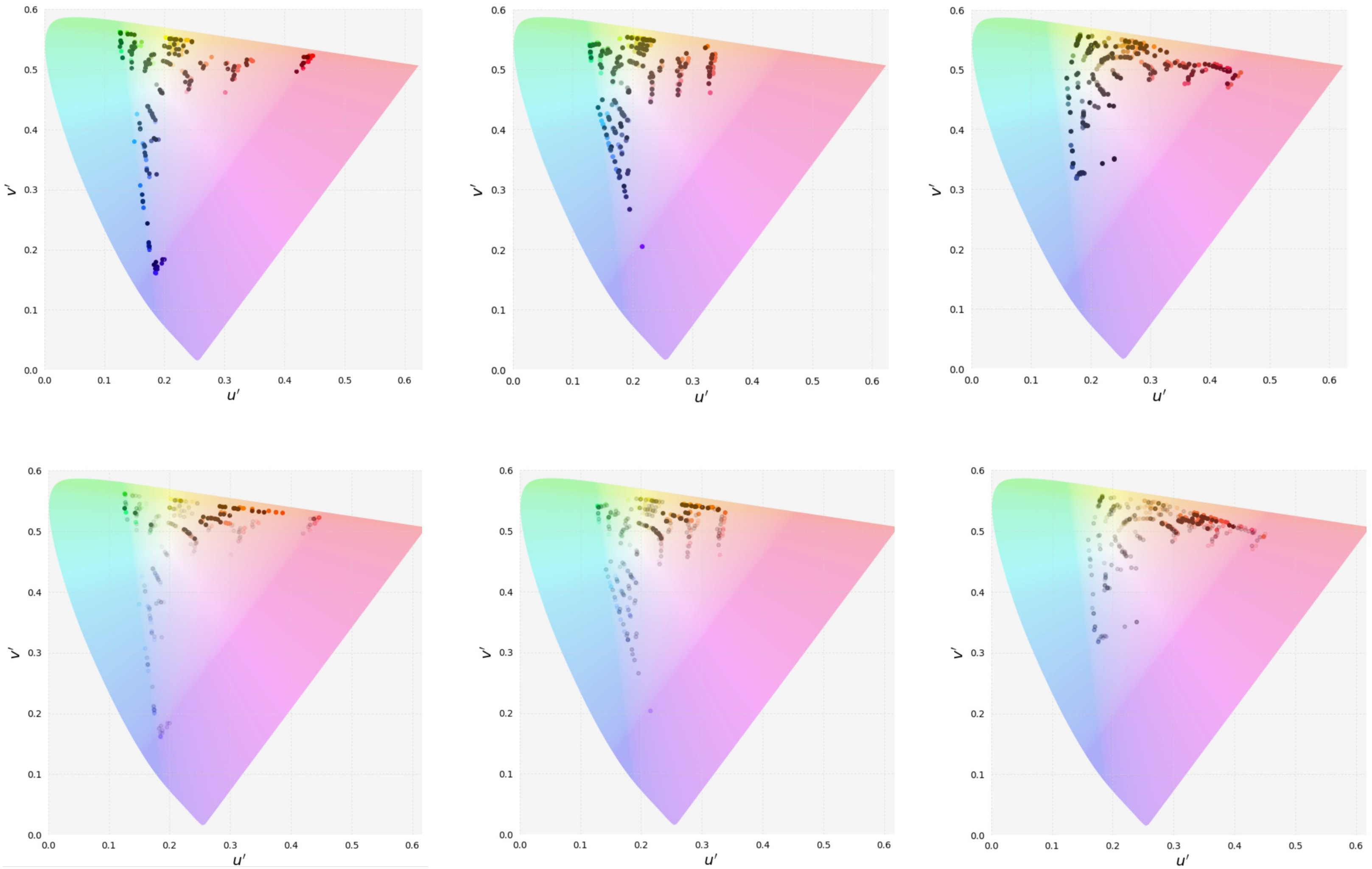
Display 1

Display 2

Display 3

Unique hues

Orange hue



- Orange hue selections are less variable between observers
  - *(Bosten and Boehm, 2014) (Bosten and Lawrance-Owen, 2014) (Wool et al., 2015) (Arstila, 018) (Witzel and Gegenfurtner, 2018)*