Adapting Color Difference for Design

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In many applications, color is critical to understanding data in context or at scale.
Color Difference for Design

Practical
Easy to construct and use

Data-Driven
Models the real world

Probabilistic
Control how noticeable differences are

Parametric
Tuned to a desired audience
Contributions

Data-Driven Method for Adapting Color Difference

Color Difference Metric for Web Viewing
Model Problem: Web Viewing
Text Legibility
Zuffi et al, 2009

Graphical Perception
Heer & Bostock, 2010

Color Names
Munroe, 2010

Contrast
Simone et al, 2010
CIELAB

Commonly used in design products
D3, Adobe

Approximately perceptually linear

Euclidean difference
Make informed decisions about color for design that hold across a variety of viewing conditions.
Make informed decisions about color for design that hold across a variety of viewing conditions.
Consider Environmental Factors in Aggregate
Model by Sampling

Laboratory metrics err by 37%
Our model predicts to within 0.2%
Verify modeling assumptions

Parameterize CIELAB

Verify the approach
Verify modeling assumptions

Parameterize CIELAB

Verify the approach
Properties of CIELAB

A1: Axes are orthogonal

A2: Difference is Euclidean

A3: Axes are uniform

A4: One unit is one JND

\[ \Delta E^* = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \]
Color Matching
Results

Errors varied **between axes** \((p > .0001)\), but no evidence of variance **within axes** \((p_L = .21, p_a = .17, p_b = .67)\).
Limitations

Not Probabilistic

Speed
We need a microtask!

Short-duration, simple piecework tasks

Precise
  Probabilistically quantify color difference

Quick
  Collect large amounts of data in a short time
Verify modeling assumptions

Parameterize CIELAB

Verify the approach
Forced-Choice Microtask

Do the two colors appear the same or different?
Forced-Choice Microtask

Do the two colors appear the same or different?
Parameterizing Color Difference

Scale each axis such that p% of viewers will identify a difference at $d = 1$
One square was mapped to a constant color.
The second square’s color was jittered from the constant along one color axis.
Color Difference

Discriminability

Color Difference
Deriving Model Parameters

Colors are $d\Delta E^*$ different

Colors were identified as different in 3 of 5 trials

The discriminability rate at $d$ is 60%
A3: Axes are uniform
Color Difference ($d$)

Discriminability Rate ($p$)

$ND_x(p) = \frac{p}{V_x}$
A1: Axes are orthogonal
Adapted Difference Model

\[ \Delta E_p = \sqrt{\left( \frac{\Delta L}{ND_L(p)} \right)^2 + \left( \frac{\Delta a}{ND_a(p)} \right)^2 + \left( \frac{\Delta b}{ND_b(p)} \right)^2} \]

\[ \Delta E^* = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \]

**A2:** Difference is Euclidean
Experiment Details

13 Color Differences x 3 axes (Within)

75 participants (2,925 trials, $\mu_{\text{trial time}} = 5.8s$)

CIELAB calibrated to sRGB
Validating Responses

Two-way ANCOVA to verify assumptions hold

Validation Stimuli
(20 equal color, 2 extreme difference)

Question order and display distance as covariates
Statistical Results

No significant variation within $a^*$ or $b^*$

0.3% linear variation in $L^*$, $p < .05$

Differences varied between all axes $p < .001$
Adapted Difference Model

$$\Delta E_{50} = \sqrt{\left(\frac{\Delta L}{4.0}\right)^2 + \left(\frac{\Delta a}{5.5}\right)^2 + \left(\frac{\Delta b}{6.0}\right)^2}$$

$$ND_L\,(50\%) = 4.0$$
$$ND_a\,(50\%) = 5.5$$
$$ND_b\,(50\%) = 6.0$$
Verify modeling assumptions

Parameterize CIELAB

Verify the approach
Verifying our Adapted Model

Denser Color Sampling  891 Cross-Axis Differences  161 participants (6,279 trials)
Results

$\Delta E_{50}$

Predicted: 50.0%
Actual: 49.8%
Results

$\Delta E_{80}$

Predicted: 80.0%
Actual: 80.6%
Limitations

Sampling Robustness

Access to a Sample
On-Going Work

Integrate into Design Tools

Stimulus Size

Talk Tomorrow: 2:40pm
Future Work

- Background Color
- Model Different Applications
Contributions

Data-Driven Method for Adapting Color Difference

Color Difference Metric for Web Viewing
Thank You!

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Traditional Color Matching

Given:

Maxwell Color Matching Experiment
Traditional Color Matching

Given:

Modern Maxwell Color Matching Experiment
Simplified Color Matching

2° Reference Color

Slider (L*, a*, or b*)

2° Response Color
Reference square was mapped to a constant color based on the tested axis.
Experiment Details

24 Reference Colors \( \times \) 3 Axes

(Within) (Between)

48 participants with no known CVD (1,032 trials)

\( \gamma = 2.2, \) D65 Whitepoint

Measure: Euclidean distance between the reference and response colors

Two-way ANCOVA with Question order and display distance as covariates
Properties of CIELAB

ΔE* = √ΔL² + Δa² + Δb²

A1: Axes are orthogonal

A2: Difference is Euclidean

A3: Axes are uniform

A4: One unit is one JND

ΔE* = 0
ΔE* = 1
ΔE* = 2
\[ ND_L(p) = \frac{p}{0.123} \]

\[ R^2 = 0.9435 \]

\[ ND_a(p) = \frac{p}{0.09194} \]

\[ R^2 = 0.9194 \]

\[ ND_b(p) = \frac{p}{0.09364} \]

\[ R^2 = 0.9364 \]
Aggregate Results

\[ \Delta E_5 - \Delta E_{95} \]
\[ \text{Mean Error: 7\%} \]

\[ \Delta E_{p \geq 50} \]
\[ \text{Mean Error: 3.5\%} \]

Expected Margin of Error = 7.5\%
Caveat:
Only model differences while discriminability is changing

Asymptote
Verifying our Adapted Model

- Differences across multiple axes
- Wider range of colors
- Greater variety of color differences
- Larger sample population
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Parametric
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Digital displays are everywhere
Existing Metrics

- CIELAB $\Delta E^*$
- $\Delta E_{94}$
- CIEDE2000
- CIECAM02
Consider Environmental Factors Individually

CRT v. LCD—Sakar et al, 2010

Individual Observers—Oicherman et al, 2008

Ambient Illumination—Devlin et al, 2006

Cockpits & Graphic Design—X,Y
Discriminability

Color Difference

$p\%$ of viewers will identify a difference at $d = 1$
Models Converge Quickly
Verifying our Adapted Model

Models hold if p% of participants correctly identify a difference at $\Delta E_p = 1$
Properties of CIELAB

A1: Axes are orthogonal

A2: Difference is Euclidean
\[ \Delta E^* = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \]

A3: Axes are uniform

A4: One unit is one JND
\[ \begin{align*}
\Delta E^* &= 0 \\
\Delta E^* &= 1 \\
\Delta E^* &= 2
\end{align*} \]
Properties of CIELAB

\[ \Delta E^* = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \]

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