Adapting Color Difference for Design

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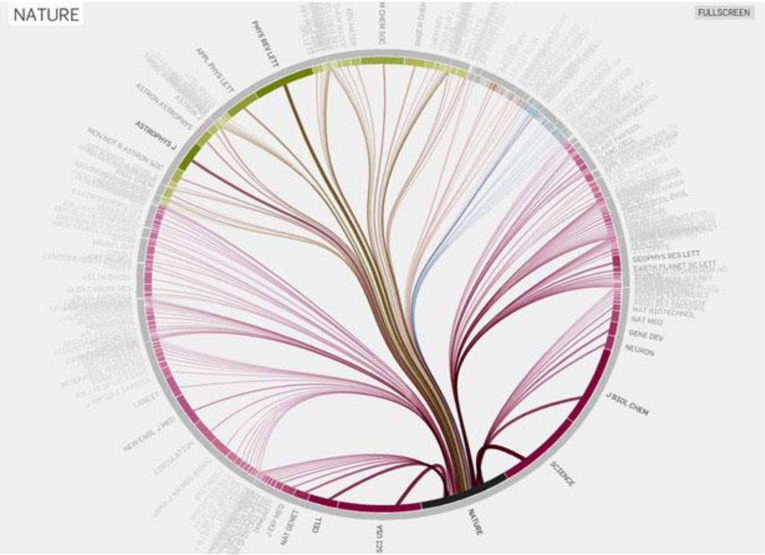
Tableau Research

University of Wisconsin, Madison Computer Graphics

tableau SOFTWARE


NATURE
FULLSCREEN
PHYS REV LETT
APPL PHYS LETT
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GEOPHYS RES LETT
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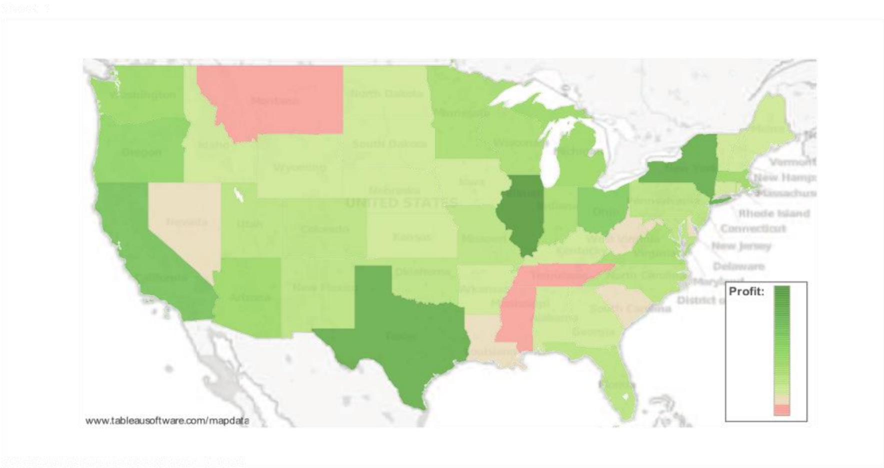
Rhode Island
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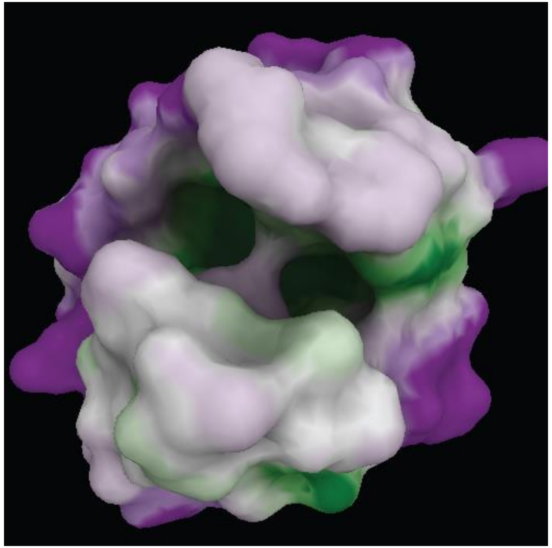
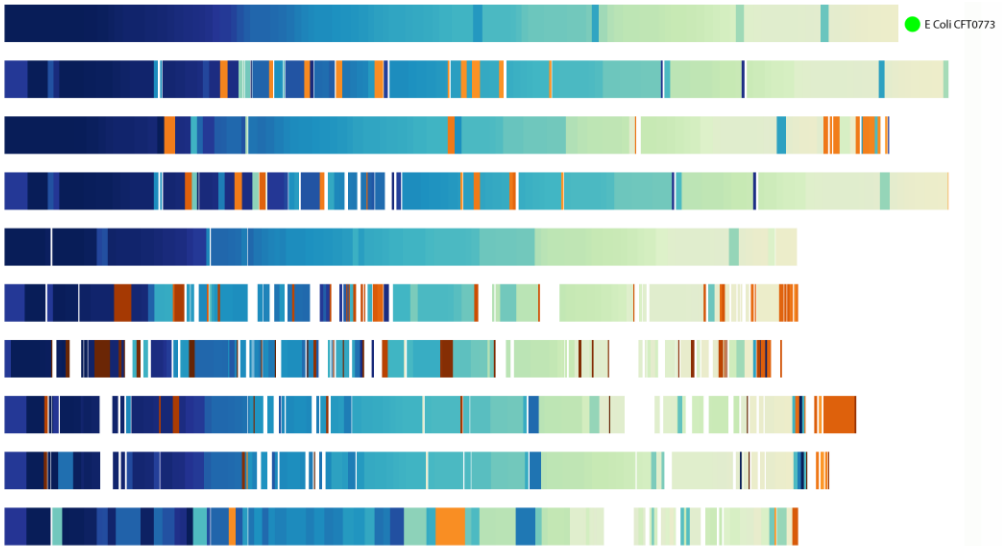
Profit:
www.tableausoftware.com/mapdata





In many applications, color is critical to understanding data in context or at scale

Color Difference for Design

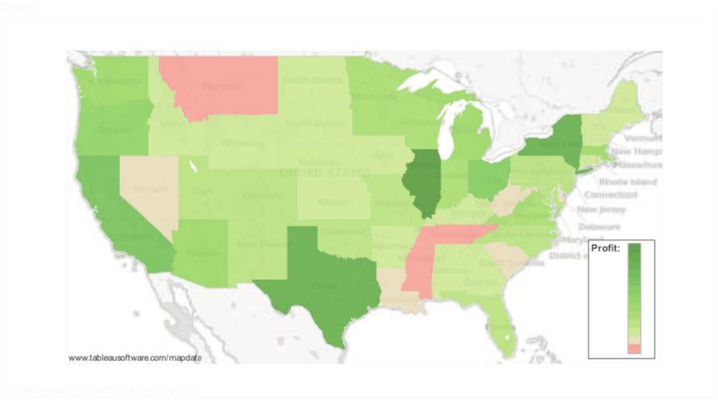
Practical
Easy to construct and use

Data-Driven
Models the real world

Probabilistic
Control how noticeable differences are

Parametric
Tuned to a desired audience

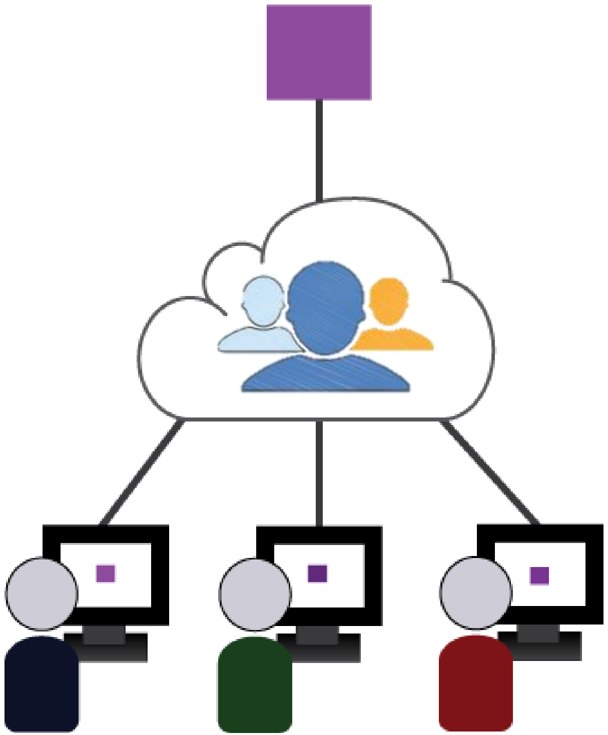
Contributions



Data-Driven Method for Adapting Color Difference

Color Difference Metric for Web Viewing

Model Problem: Web Viewing



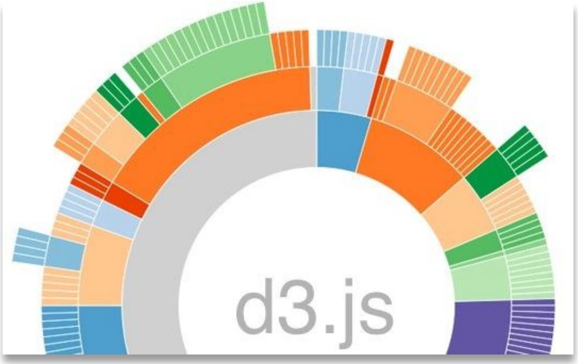
Text Legibility
Zuffi et al, 2009

Graphical Perception
Heer & Bostock, 2010

Color Names
Munroe, 2010

Contrast
Simone et al, 2010

CIELAB

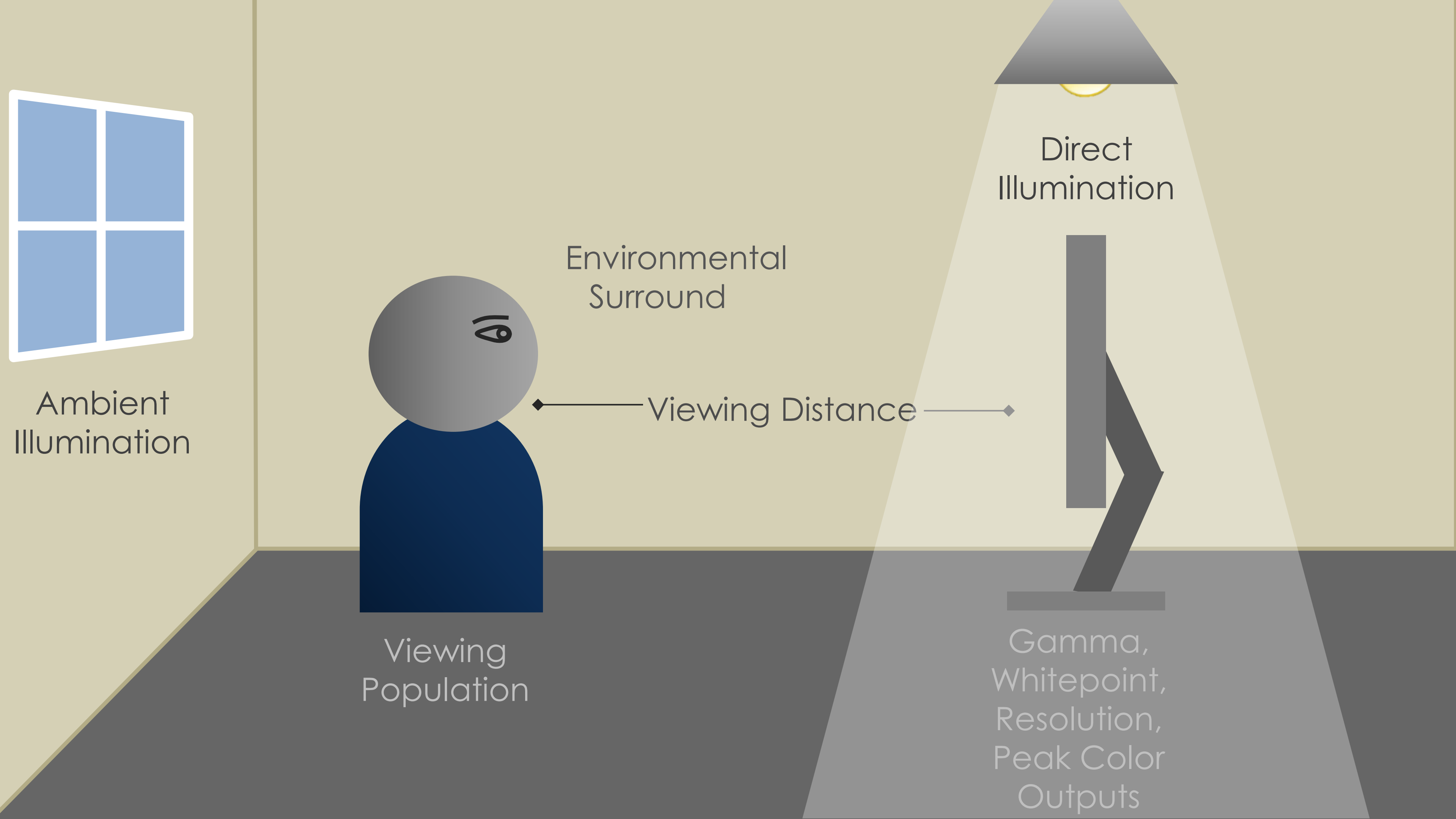


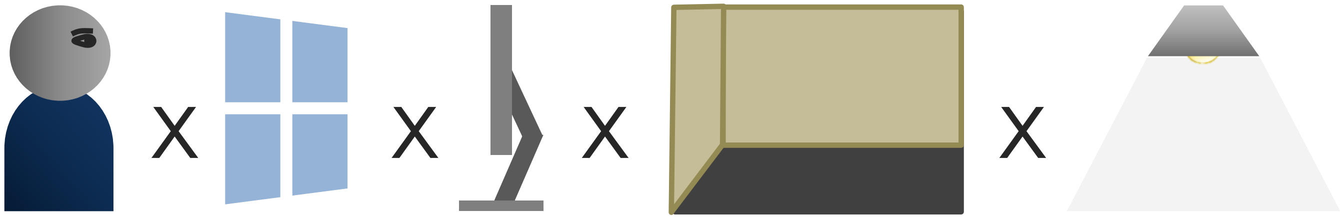
Commonly used in design products
D3, Adobe

Approximately perceptually linear

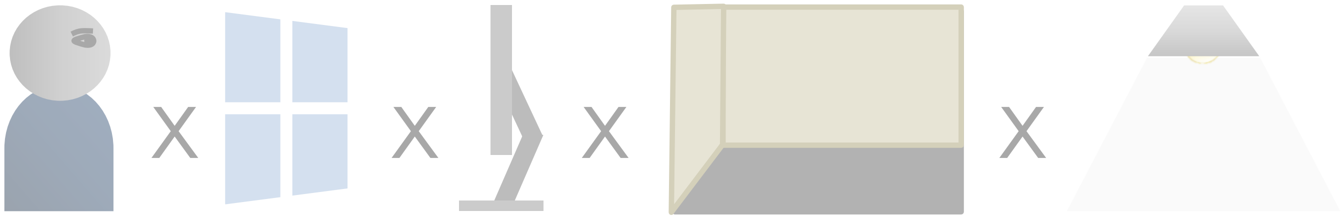
Euclidean difference

Make informed decisions about color for design that hold across a variety of viewing conditions

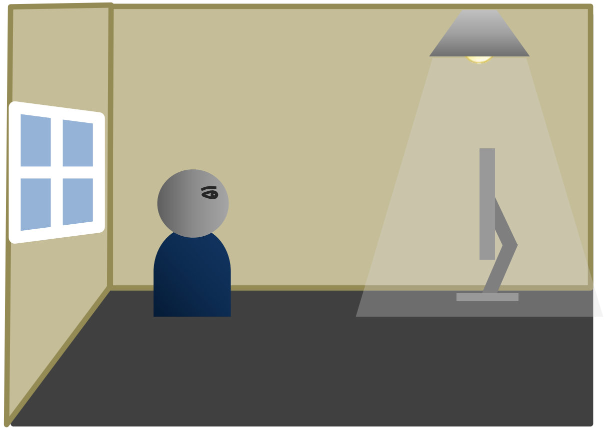

Direct Illumination
Environmental Surround
Ambient Illumination
Viewing Distance
Viewing Population
Gamma, Whitepoint, Resolution, Peak Color Outputs



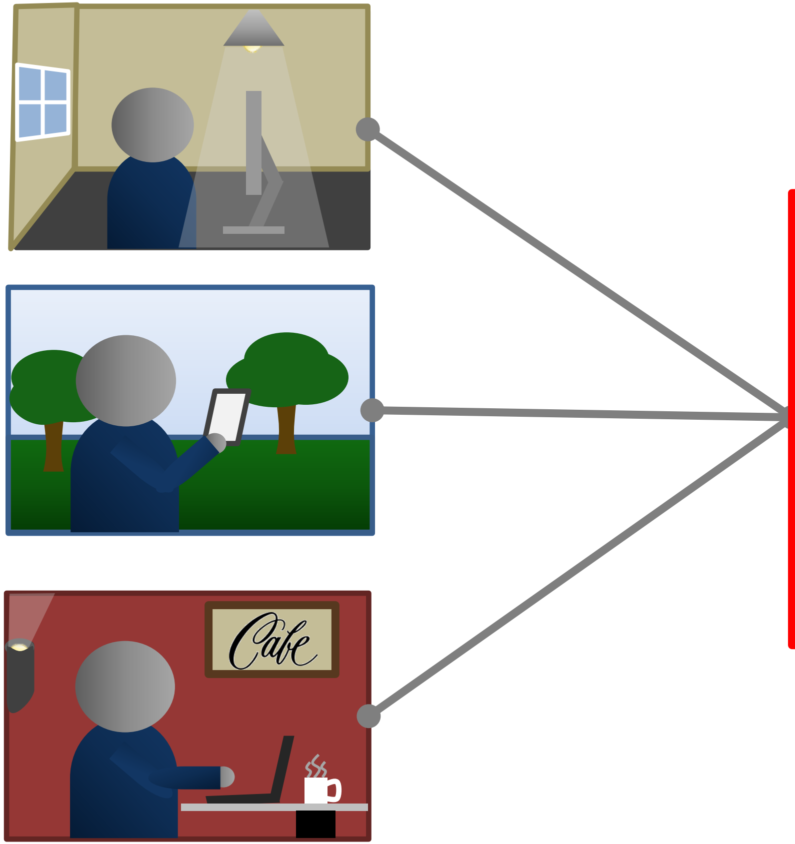
Make informed decisions about color for design that hold across a variety of viewing conditions



Consider Environmental Factors in Aggregate

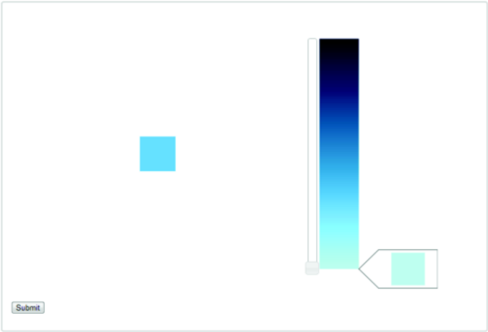


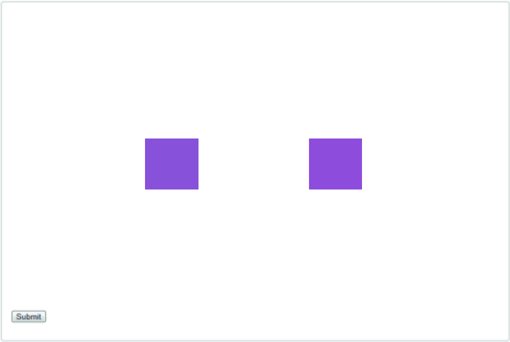
Model by Sampling



Laboratory metrics err by 37%

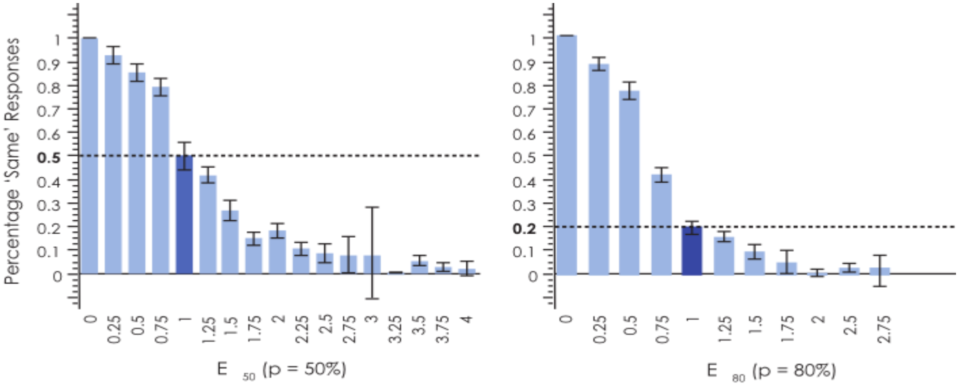
Our model predicts to **within 0.2%**



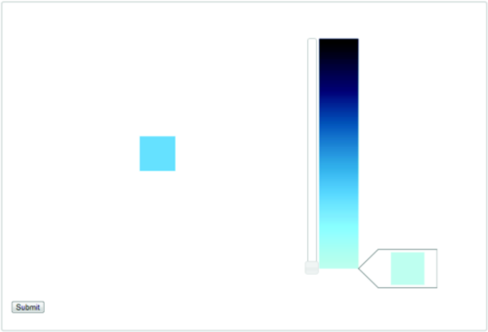


Verify modeling assumptions

Parameterize CIELAB

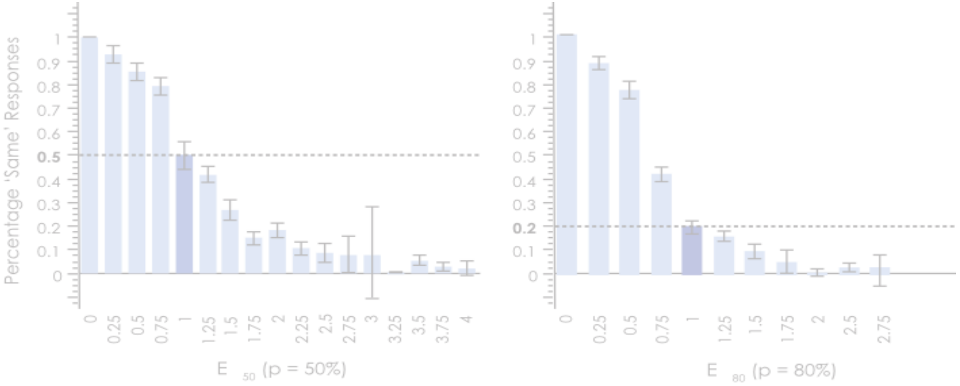


Verify the approach



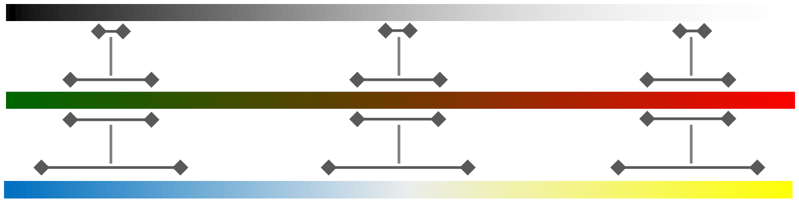
Verify modeling assumptions

Parameterize CIELAB



Verify the approach

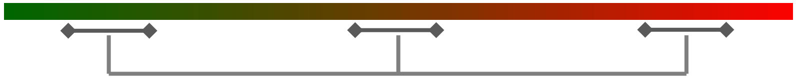
Properties of CIELAB



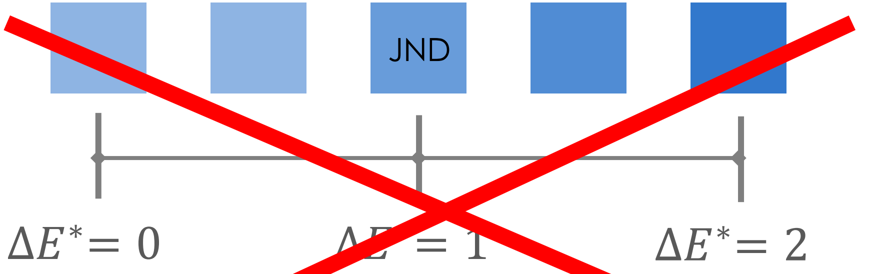
A1: Axes are orthogonal

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

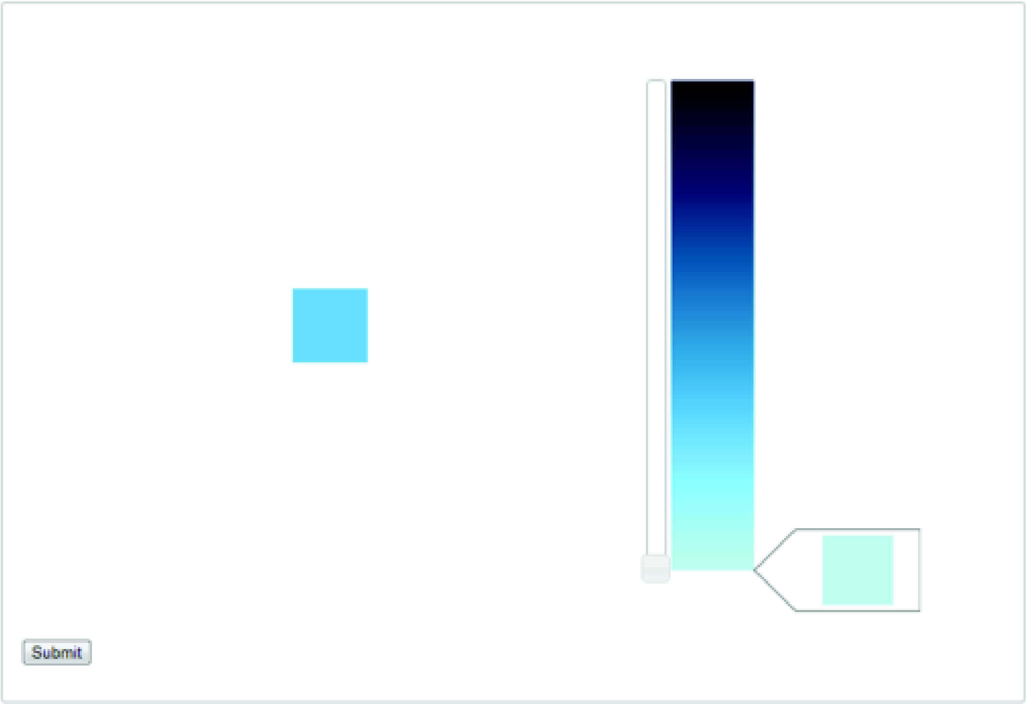
A2: Difference is Euclidean



A3: Axes are uniform

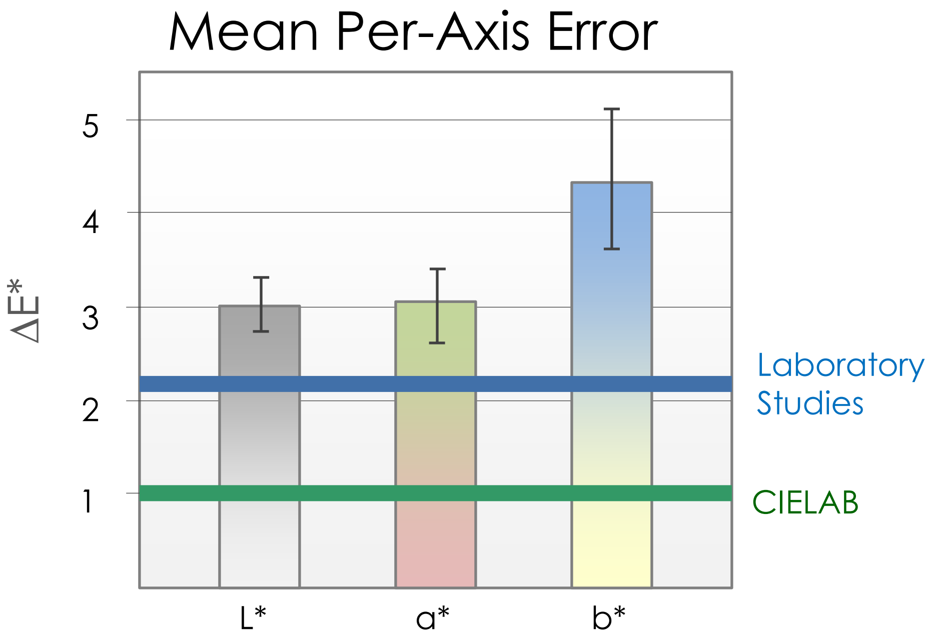


A4: One unit is one JND



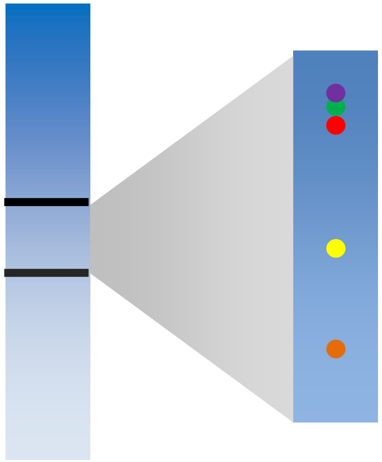
Color Matching

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!

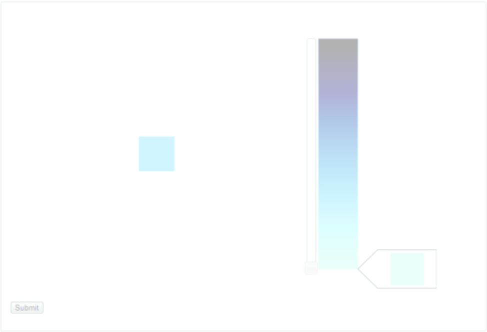
Short-duration, simple piecework tasks

Precise

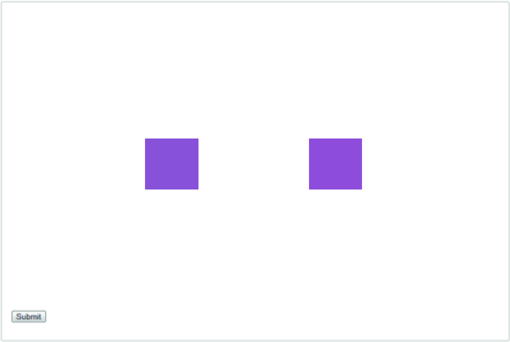
Probabilistically quantify color difference

Quick

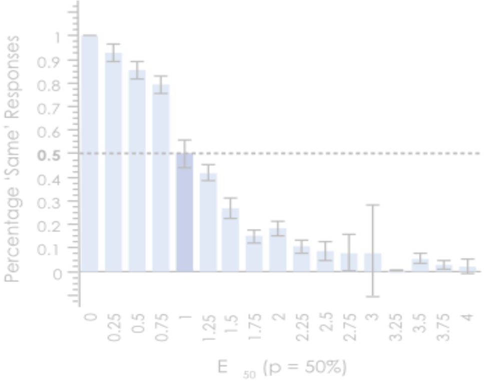
Collect large amounts of data in a short time

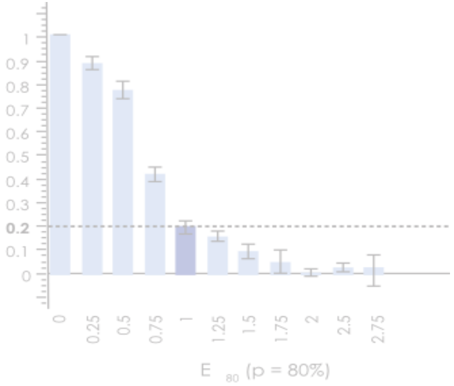


Verify modeling assumptions



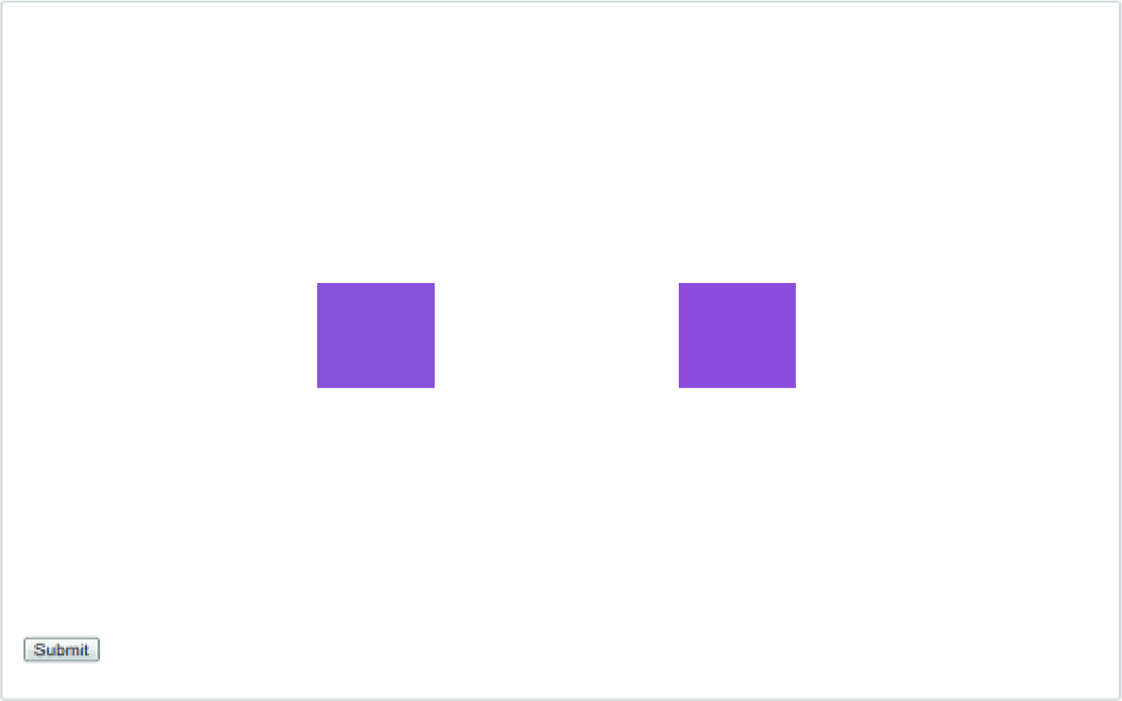
Parameterize CIELAB





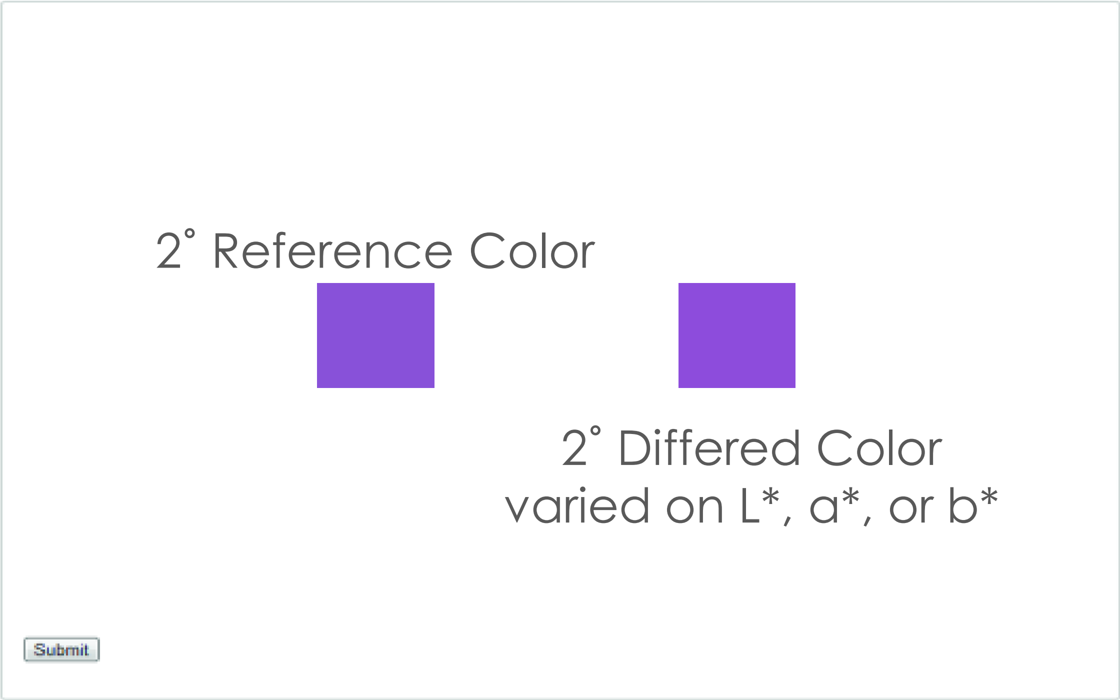
Verify the approach

Forced-Choice Microtask



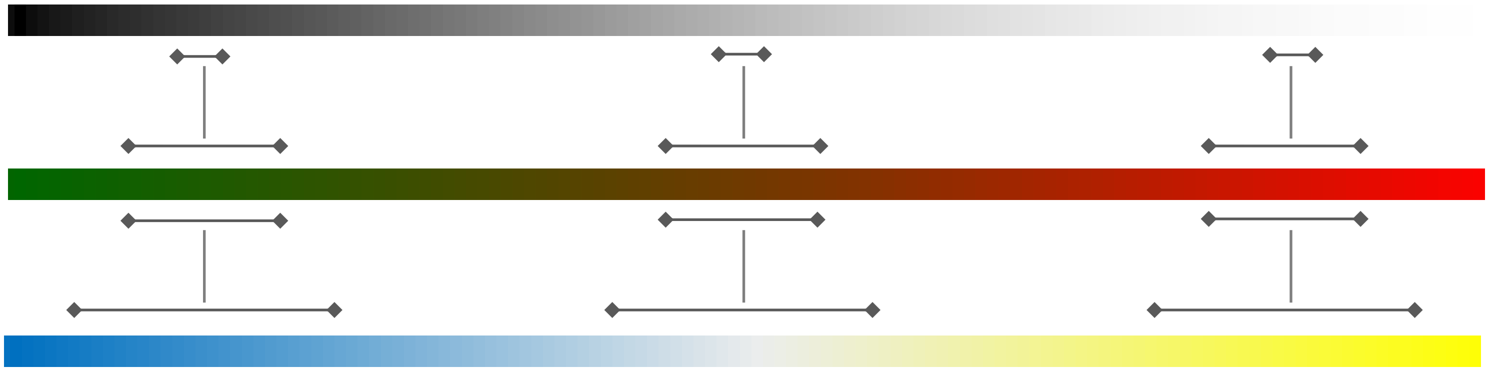
Do the two colors appear the same or different?

Forced-Choice Microtask

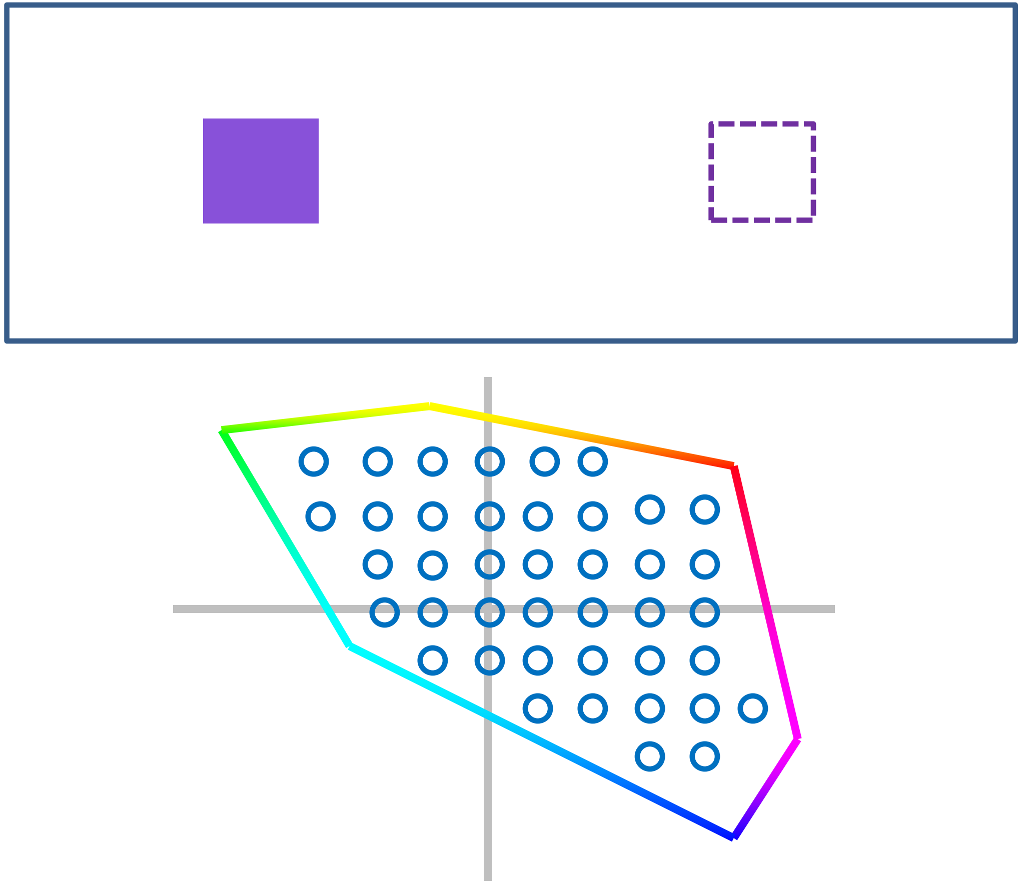


Do the two colors appear the same or different?

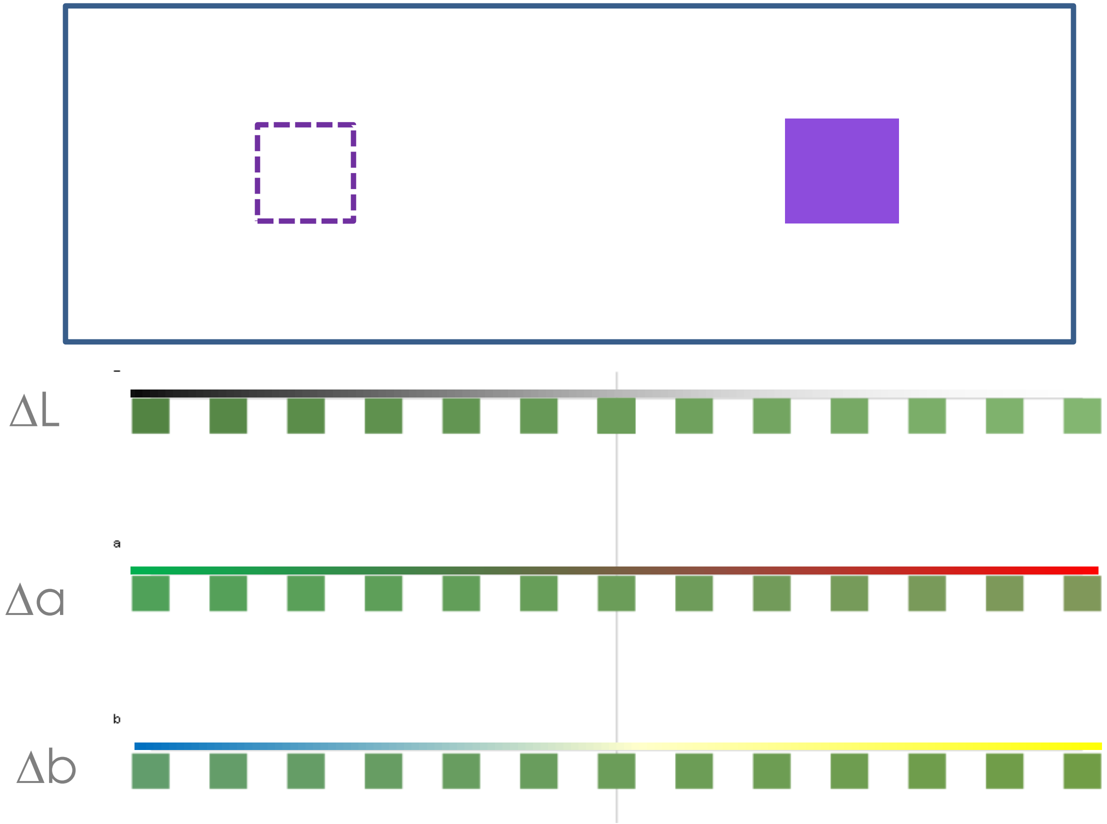
Parameterizing Color Difference



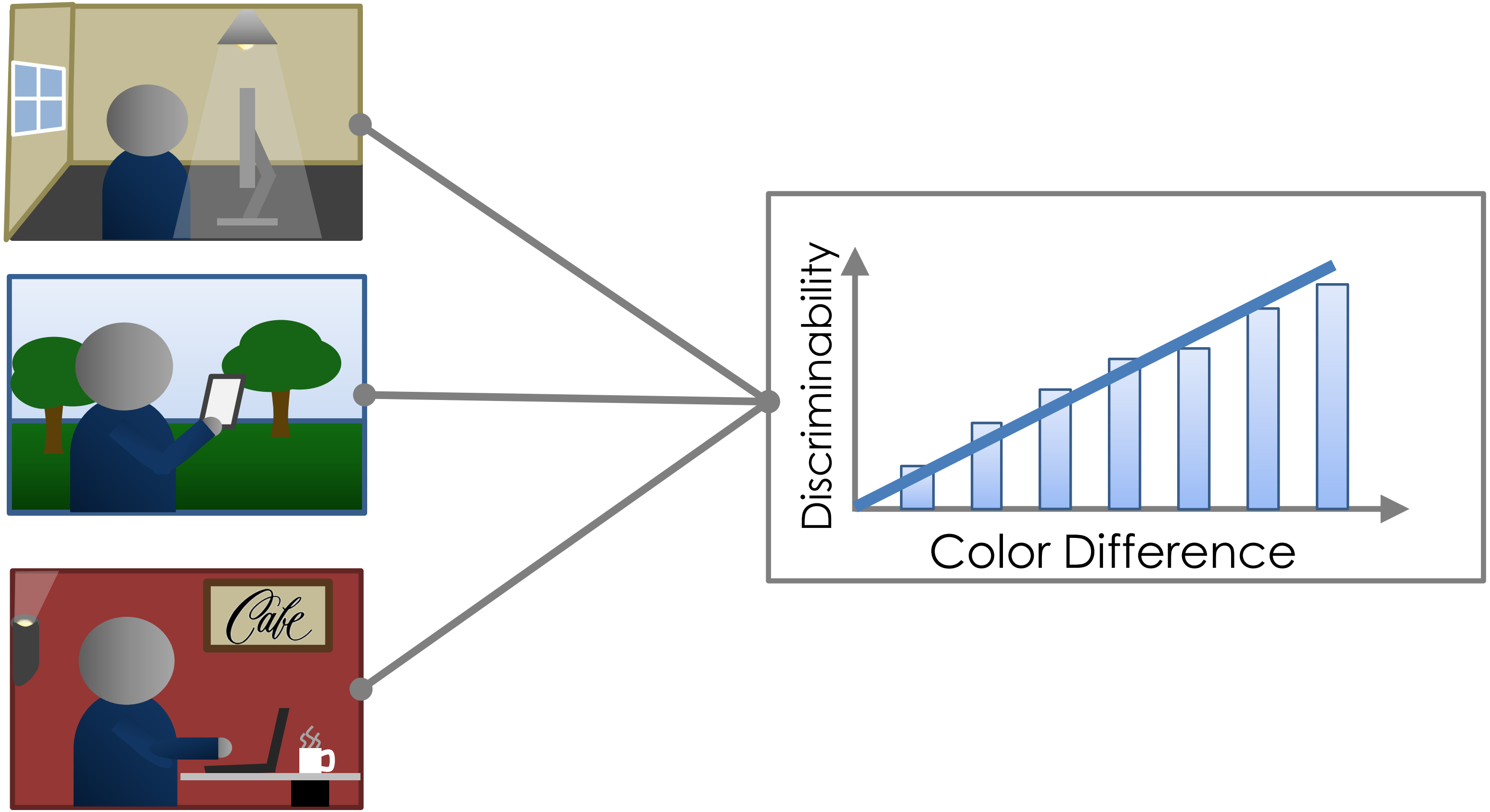
Scale each axis such that p% of viewers will identify a difference at d = 1



One square was mapped to a constant color

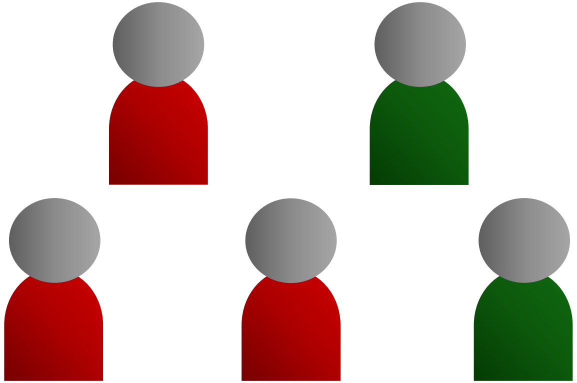


The second square's color was jittered from the constant along one color axis



Cafe
Discriminability
Color Difference

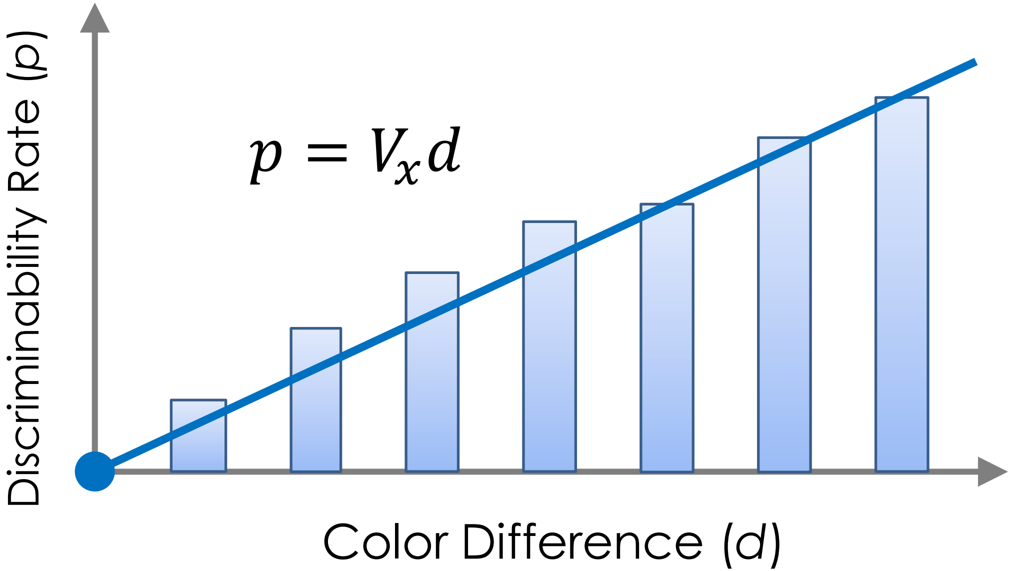
Deriving Model Parameters

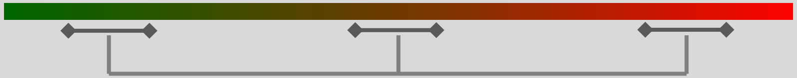


Colors are *d* ΔE* different

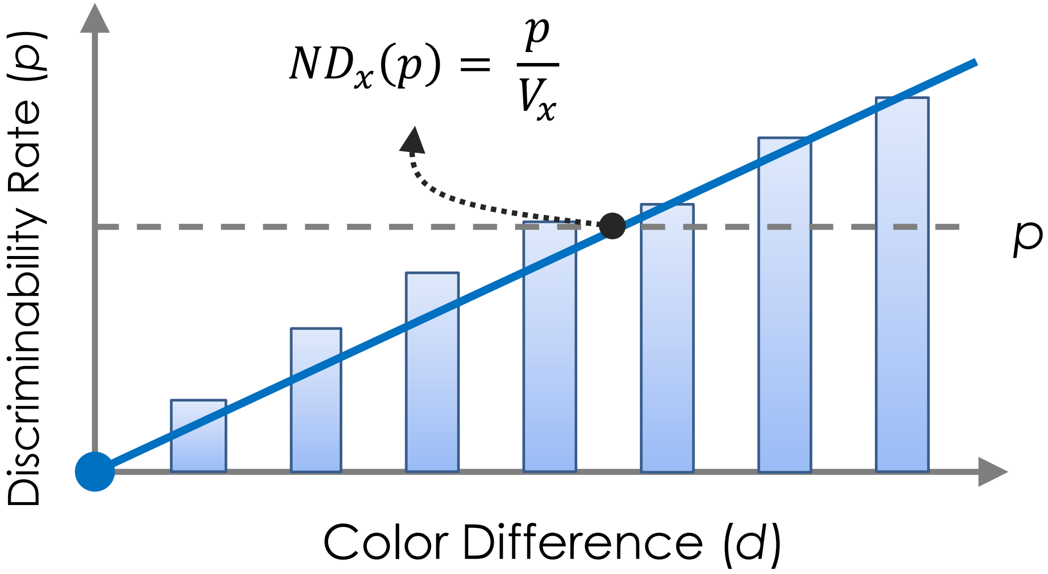
Colors were identified as different in 3 of 5 trials

The disciminability rate at *d* is 60%

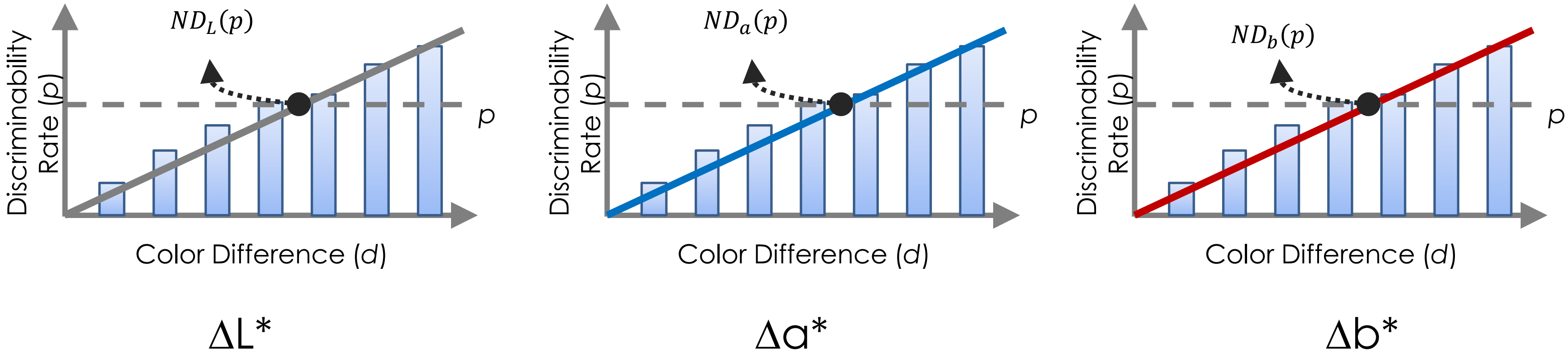




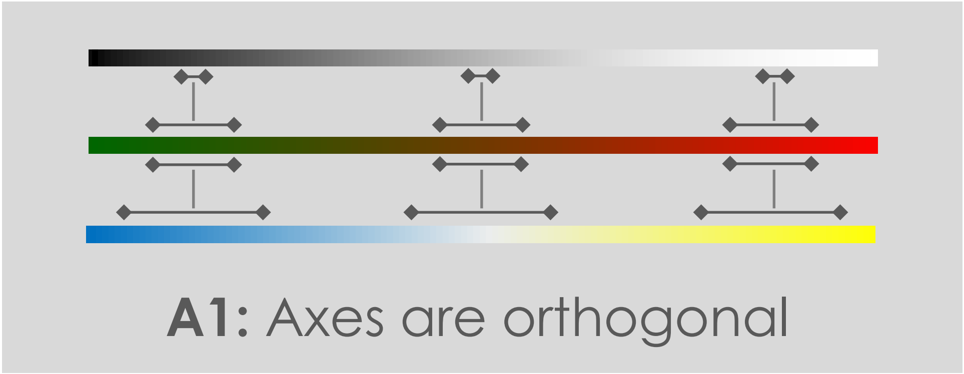
A3: Axes are uniform



$ND_x(p) = \frac{p}{V_x}$
p
Discriminability Rate (p)
Color Difference (d)



$ND_L(p)$
Discriminability Rate (p)
p
Color Difference (d)
ΔL*
$ND_a(p)$
Discriminability Rate (p)
p
Color Difference (d)
Δa*
$ND_b(p)$
Discriminability Rate (p)
p
Color Difference (d)
Δb*



A1: Axes are orthogonal

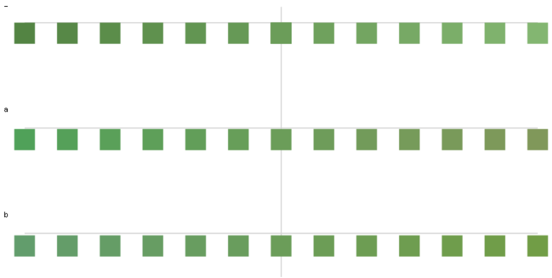
Adapted Difference Model

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

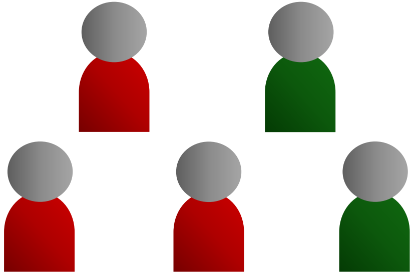
$$\Delta E^* = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$

A2: Difference is Euclidean

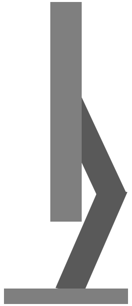
Experiment Details



13 Color Differences x 3 axes
(Within)

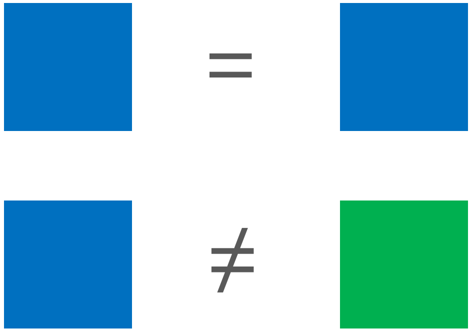


75 participants
(2,925 trials, $\mu_{trial\ time}$= 5.8s)



CIELAB calibrated to sRGB

Validating Responses

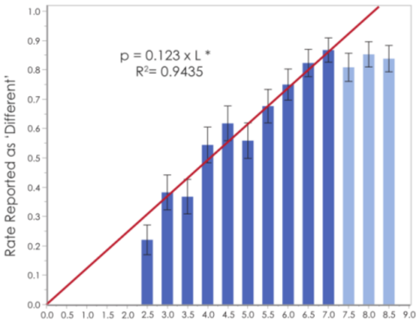


Validation Stimuli
(20 equal color, 2 extreme difference)

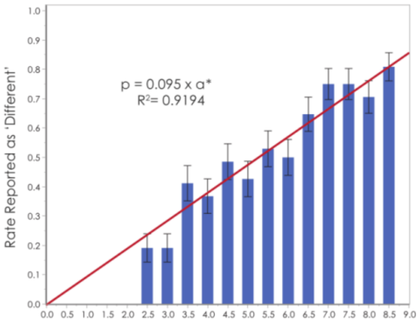
Two-way ANCOVA to verify assumptions hold

Question order and display distance as covariates

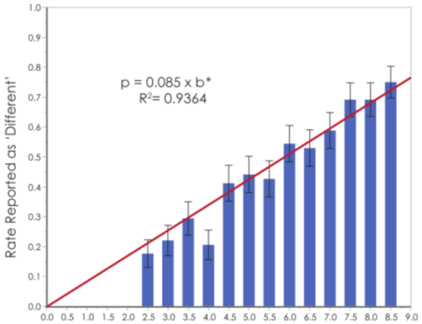
Statistical Results



$$R^2{}_L = 0.9435$$



$$R^2{}_a = 0.9194$$



$$R^2{}_b = 0.9364$$

No significant variation within a* or b*

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

Differences varied between all axes

$p < .001$

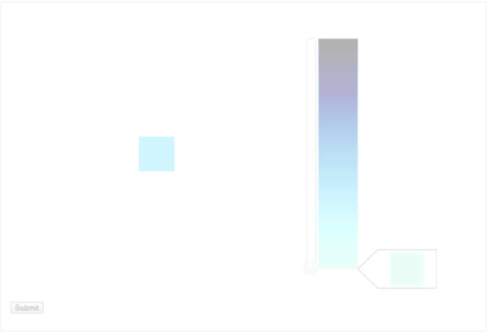
Adapted Difference Model

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

$$ND_L(50\%) = 4.0$$

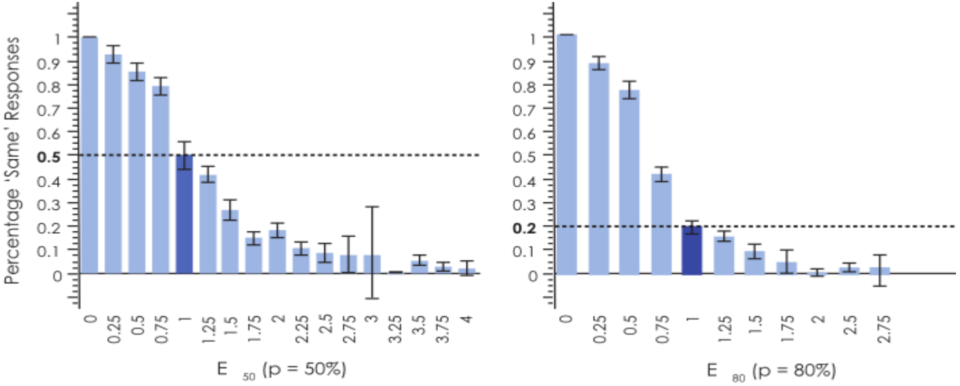
$$ND_a(50\%) = 5.5$$

$$ND_b(50\%) = 6.0$$



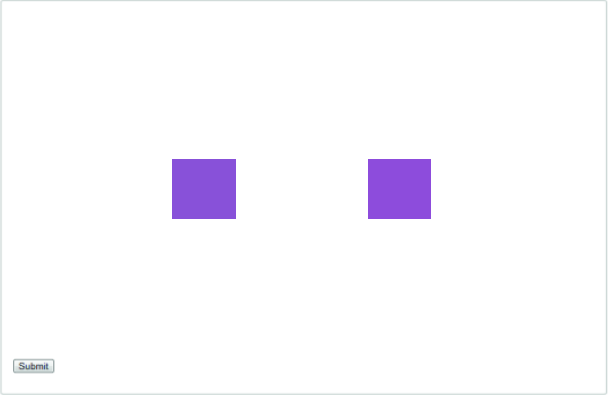
Verify modeling assumptions

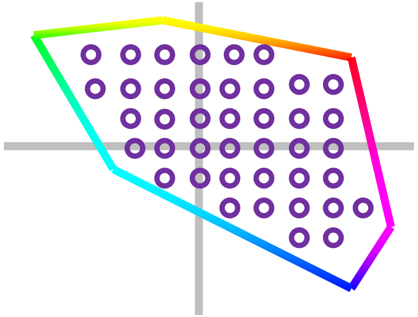
Parameterize CIELAB



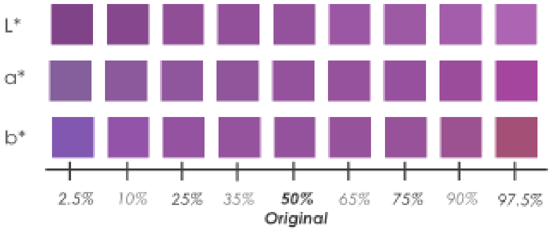
Verify the approach

Verifying our Adapted Model

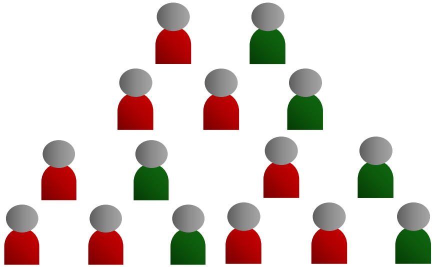




Denser Color Sampling



891 Cross-Axis Differences



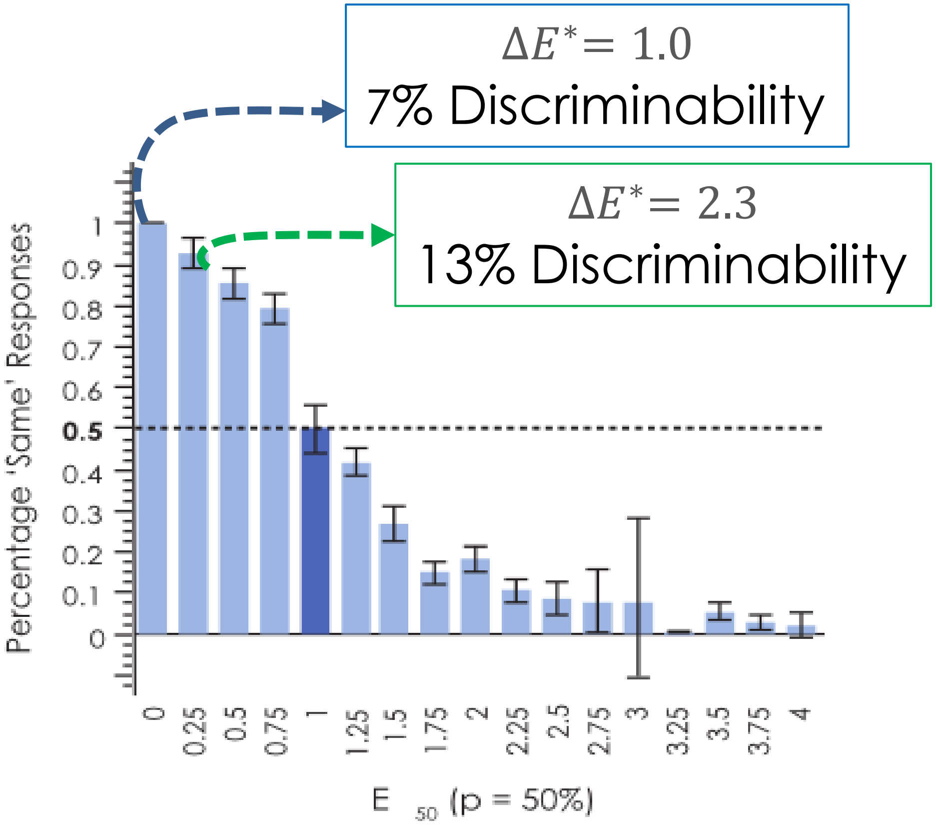
161 participants (6,279 trials)

Results

$$\frac{\Delta E_{50}}{}$$

Predicted: 50.0%

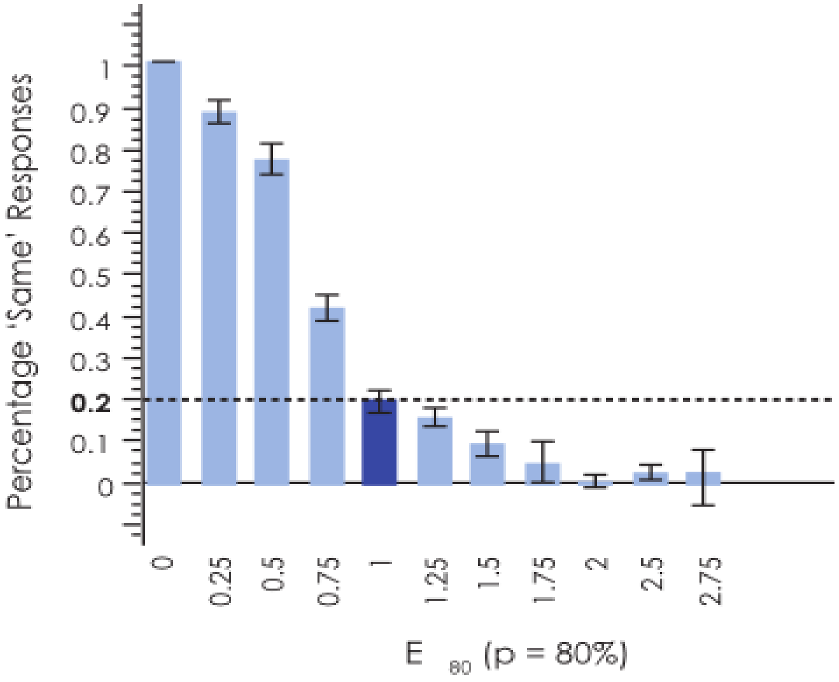
Actual: 49.8%



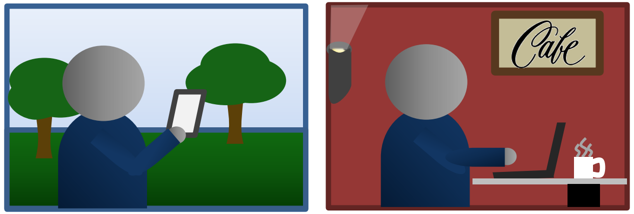
Results

ΔE_{80}

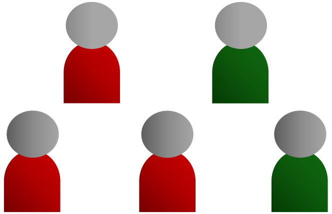
Predicted: 80.0%
Actual: 80.6%



Limitations

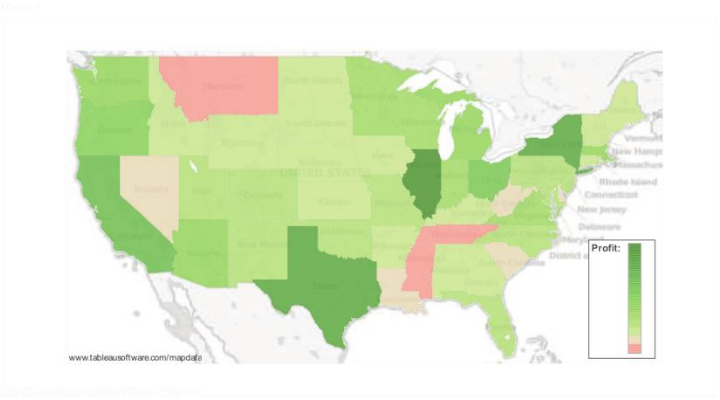


Sampling Robustness



Access to a Sample

On-Going Work

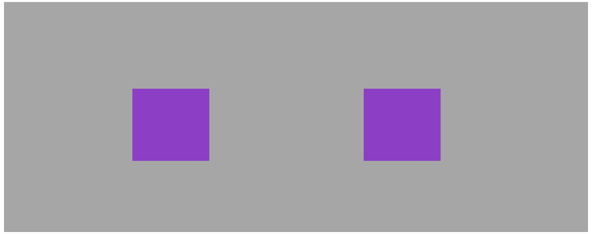


Integrate into Design Tools

Stimulus Size

Talk Tomorrow: 2:40pm

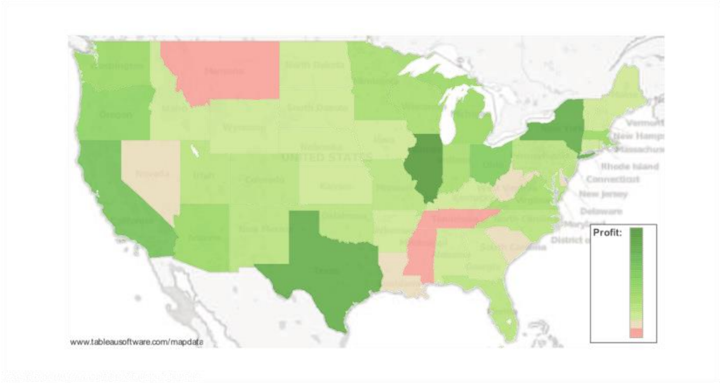
Future Work



Background Color

Model Different Applications

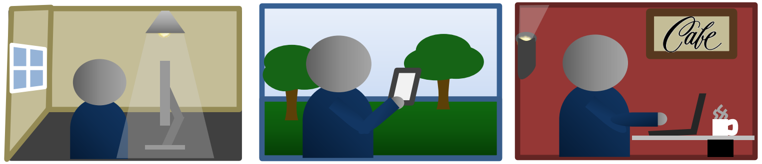
Contributions

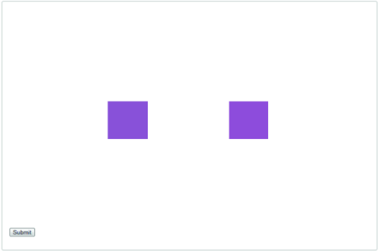


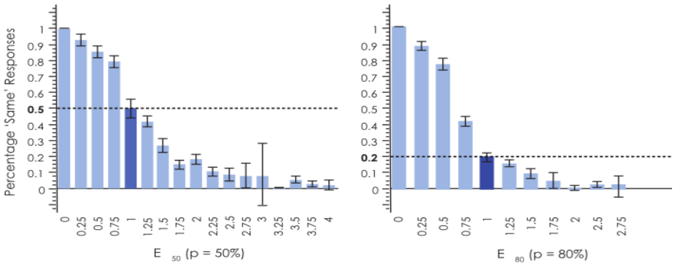
Data-Driven Method for
Adapting Color Difference

Color Difference Metric for
Web Viewing

Thank You!







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Thanks to Vidya Setlur, Justin Talbot, Dan Szafir, and the UW Graphics Group for their help with this project.

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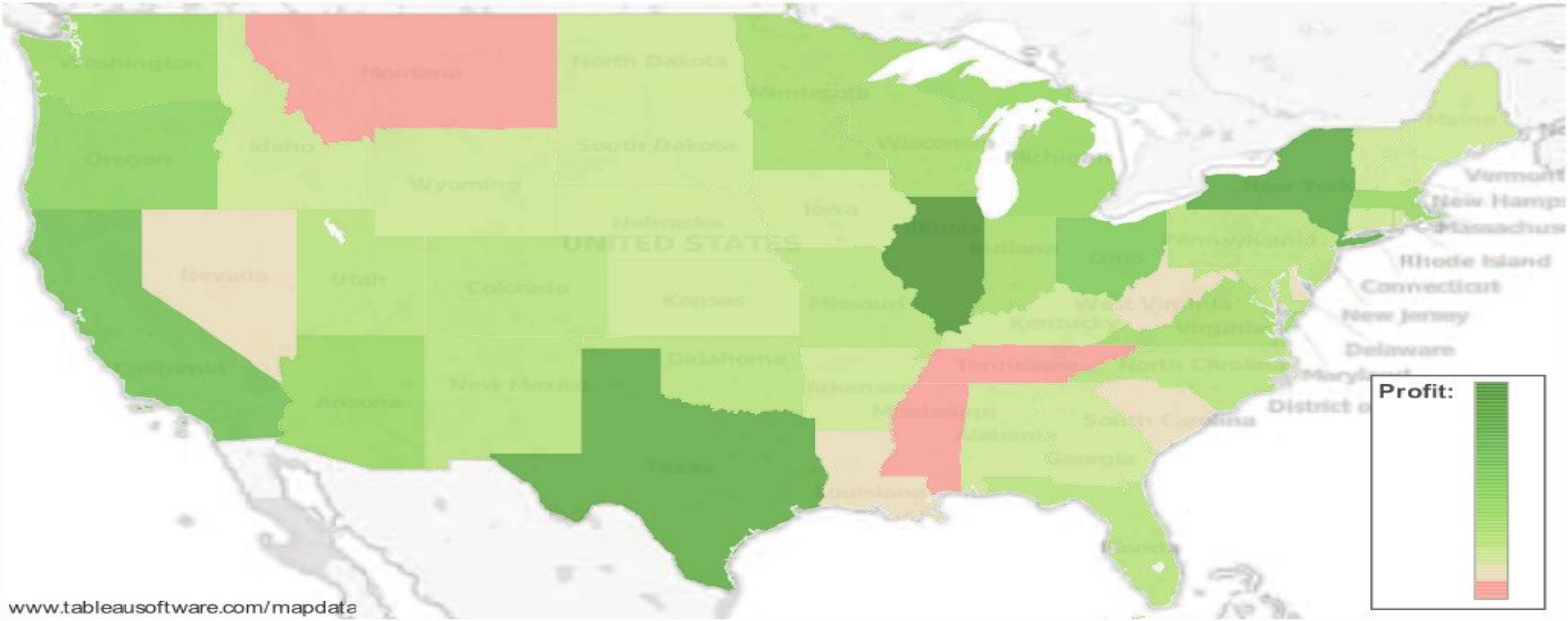
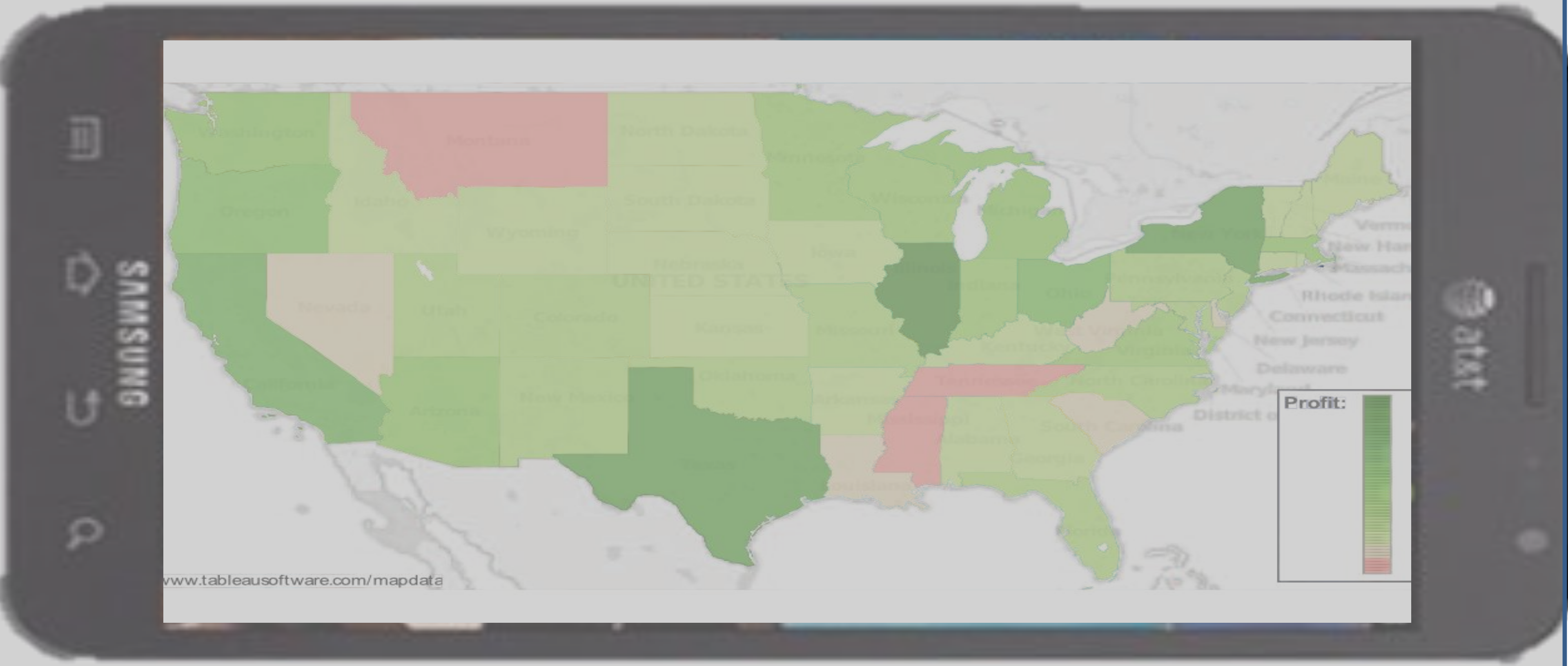
Sheet 1

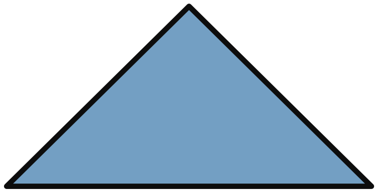


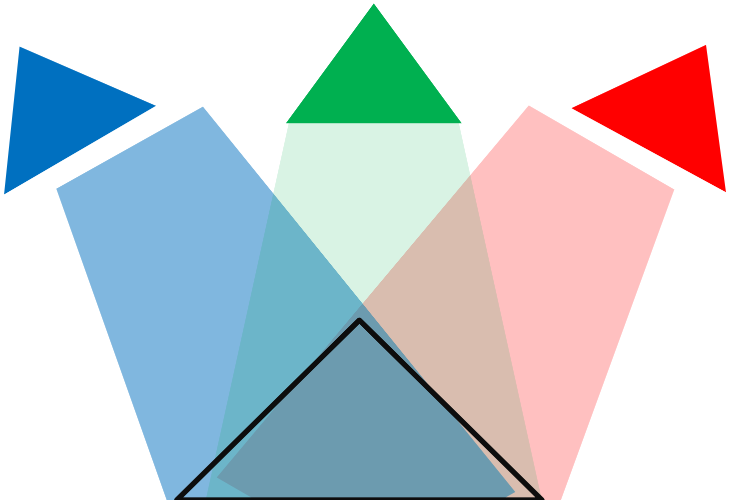
Washington
Montana
North Dakota
Minnesota
Oregon
Idaho
South Dakota
Wisconsin
Wyoming
Iowa
Nebraska
UNITED STATES
Nevada
Utah
Colorado
Kansas
Missouri
Illinois
Indiana
Ohio
New York
Pennsylvania
Kentucky
West Virginia
Virginia
California
Oklahoma
Tennessee
North Carolina
Arizona
New Mexico
Arkansas
Mississippi
Alabama
South Carolina
Georgia
Texas
Louisiana
Florida
Vermont
Massachus
Rhode Island
Connecticut
New Jersey
Delaware
Profit:
www.tableausoftware.com/mapdata


SAMSUNG
Connecticut
New Jersey
Delaware
Profit:
www.tableausoftware.com/mapdata

Traditional Color Matching

Given:

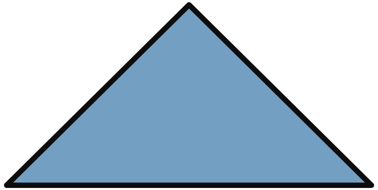


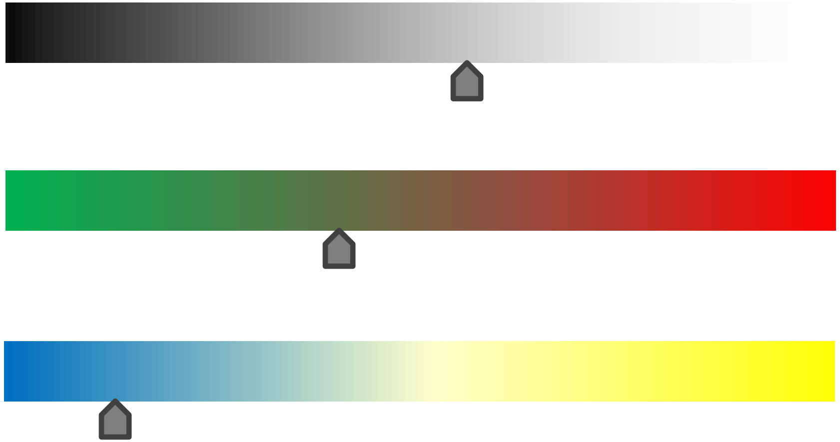


Maxwell Color Matching Experiment

Traditional Color Matching

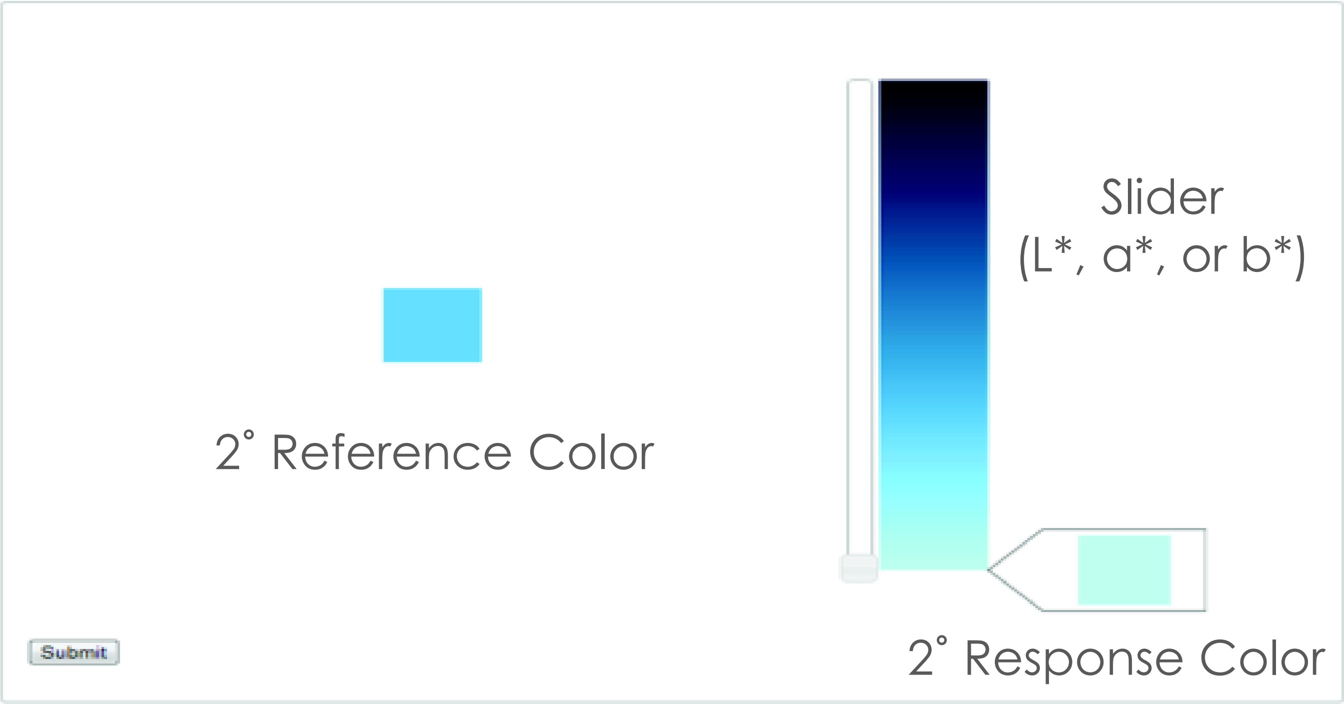
Given:

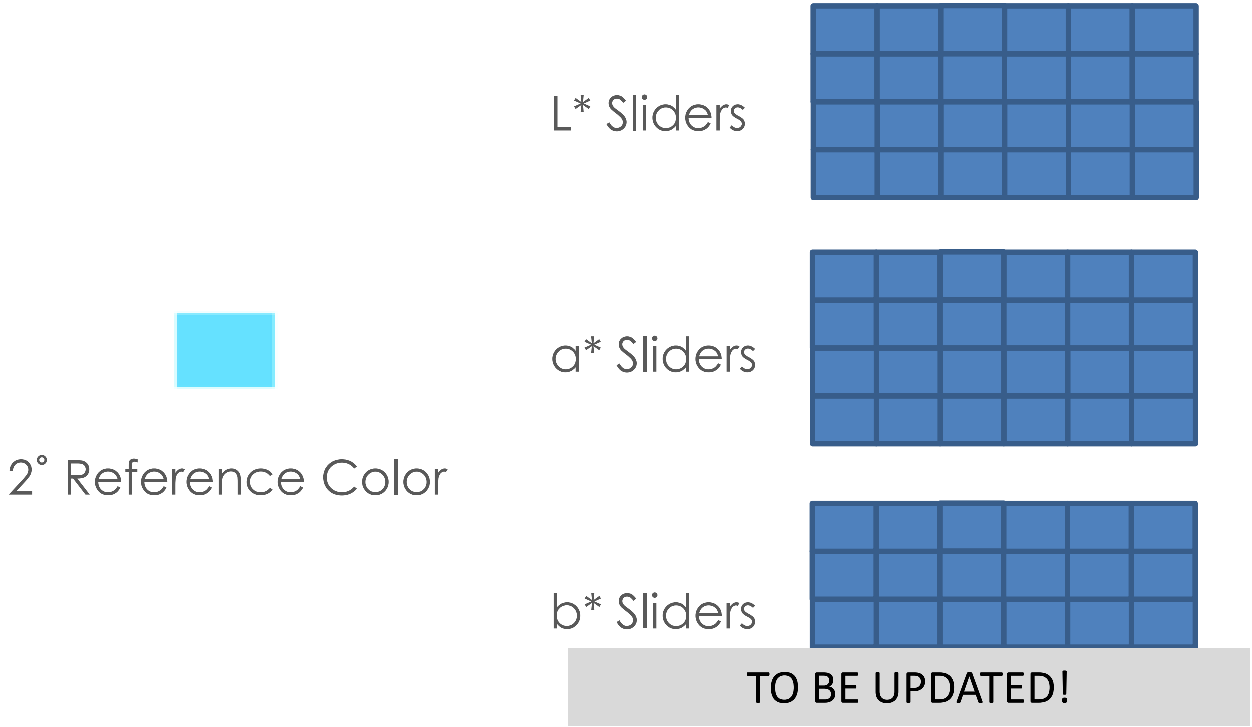




Modern Maxwell Color Matching Experiment

Simplified Color Matching





Reference square was mapped to a constant color based on the tested axis

Experiment Details

24 Reference Colors (Within) x 3 Axes (Between)

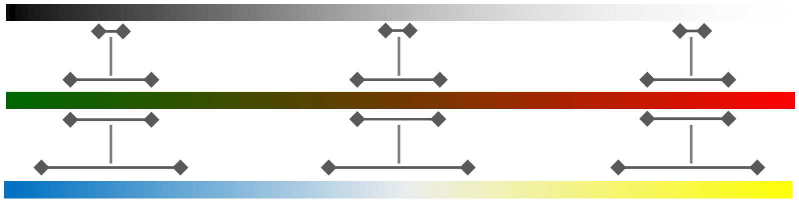
48 participants with no known CVD (1,032 trials)

$\gamma = 2.2$, D65 Whitepoint

Measure: Euclidean distance between the reference and response colors

Two way ANCOVA with Question order and display

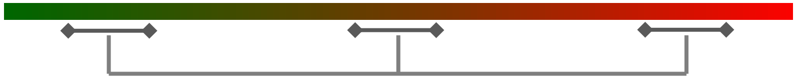
Properties of CIELAB



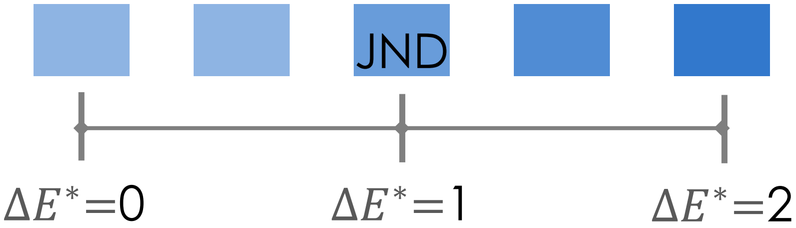
A1: Axes are orthogonal

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

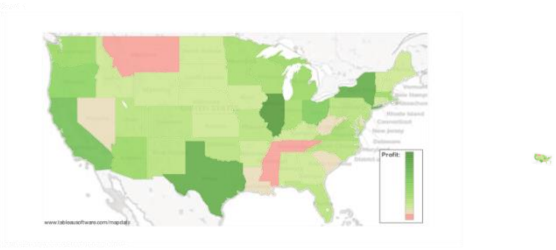
A2: Difference is Euclidean

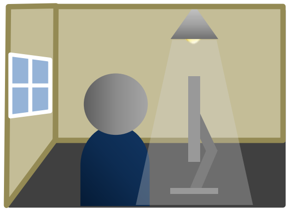


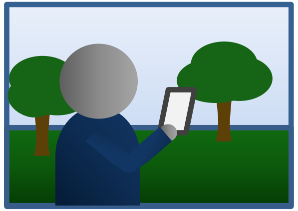
A3: Axes are uniform

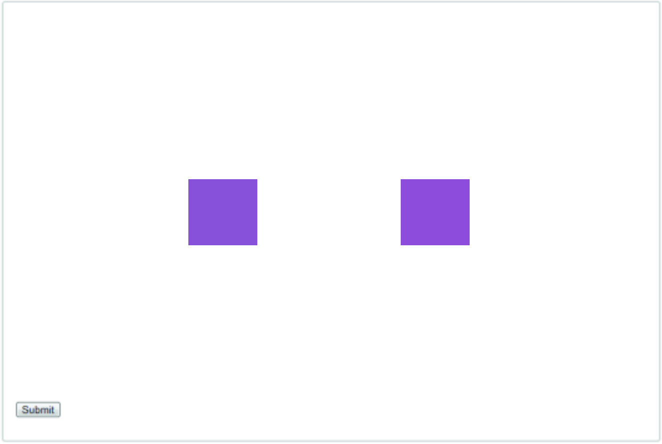


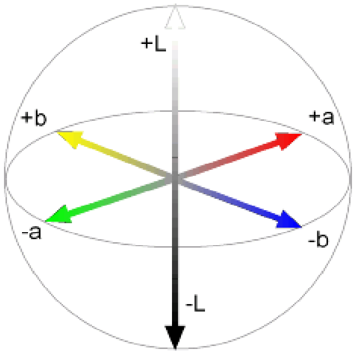
A4: One unit is one JND

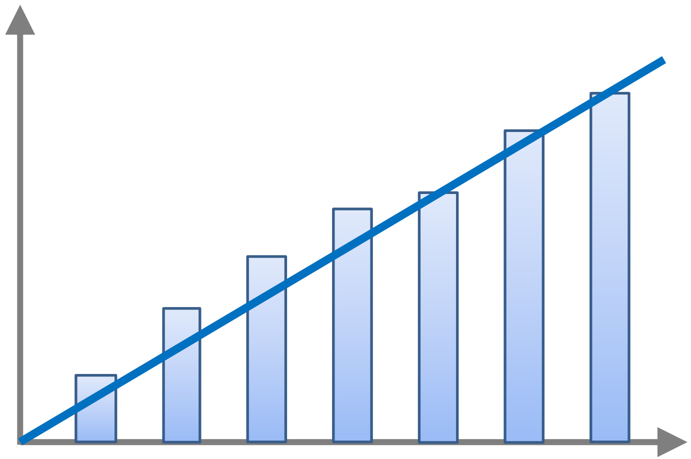




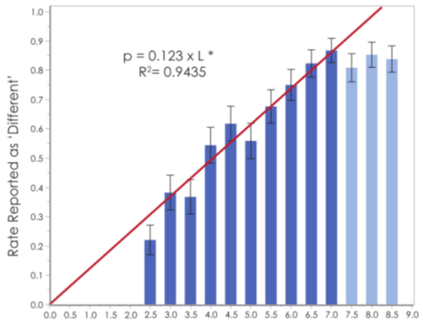



Submit

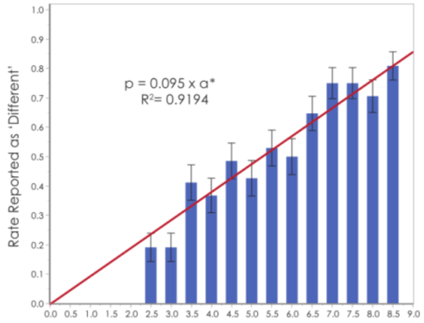

+L
+b
+a
-a
-b
-L



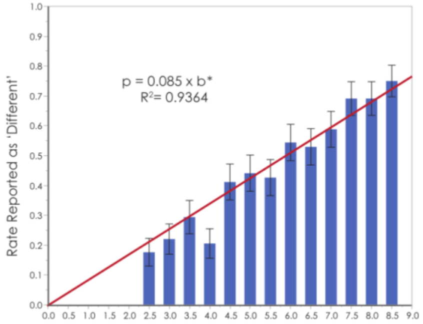
ΔL^*



Δa^*



Δb^*



$$ND_L(p) = \frac{p}{0.123}$$

$$\boldsymbol{R^2 = 0.9435}$$

$$ND_a(p) = \frac{p}{0.09194}$$

$$\boldsymbol{R^2 = 0.9194}$$

$$ND_b(p) = \frac{p}{0.09364}$$

$$\boldsymbol{R^2 = 0.9364}$$

Aggregate Results

$$\Delta E_5 - \Delta E_{95}$$

Mean Error: 7%

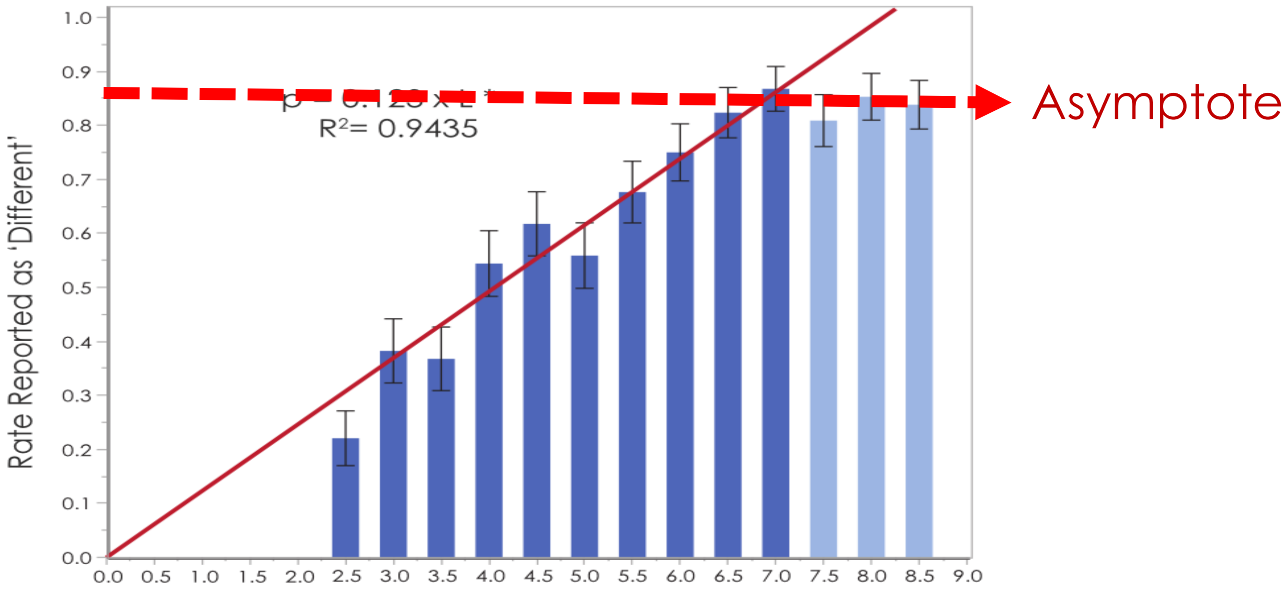
$$\Delta E_{p \geq 50}$$

Mean Error: 3.5%

Expected Margin of Error = 7.5%

Caveat:

Only model differences while discriminability is changing



Verifying our Adapted Model

Differences across multiple axes

Wider range of colors

Greater variety of color differences

Larger sample population

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

Digital displays are everywhere

Existing Metrics

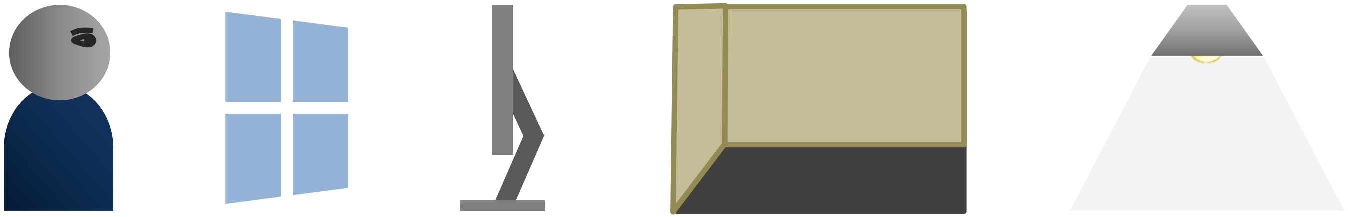
CIELAB ΔE^*

ΔE_{94}

CIEDE2000

CIECAM02

Consider Environmental Factors Individually

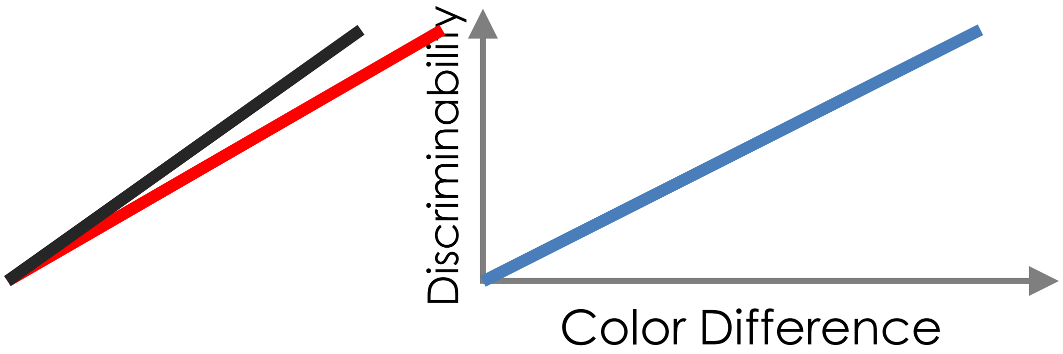


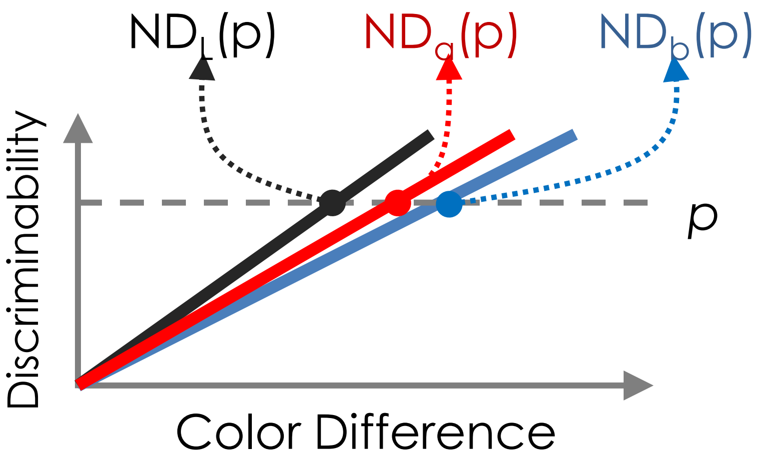
CRT v. LCD—*Sakar et al, 2010*

Individual Observers—*Oicherman et al, 2008*

Ambient Illumination—*Devlin et al, 2006*

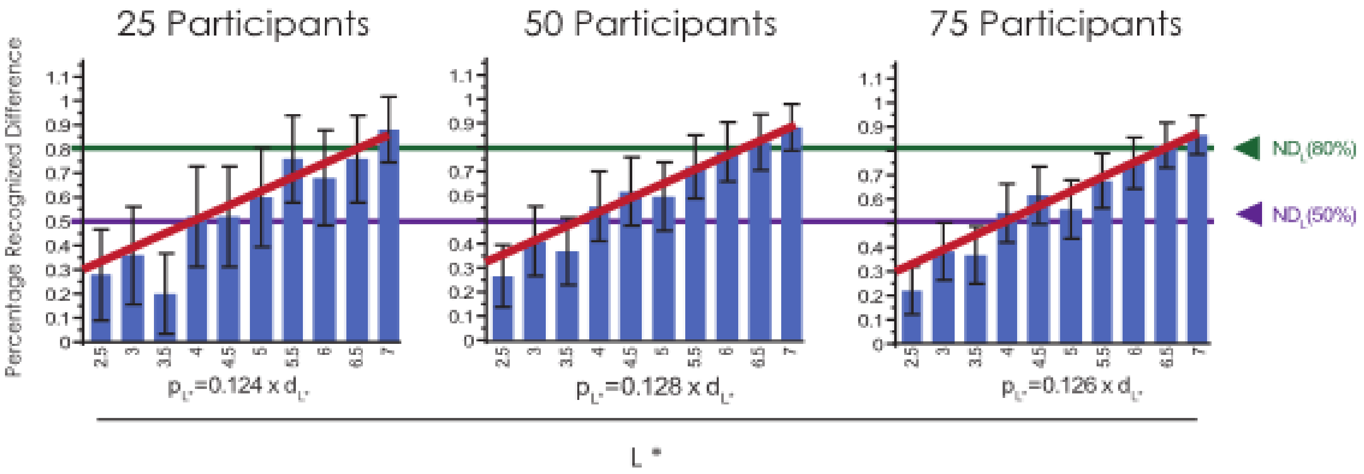
Cockpits & Graphic Design—X,Y


Discriminability
Color Difference



__p%__ of viewers will identify a difference at d = 1

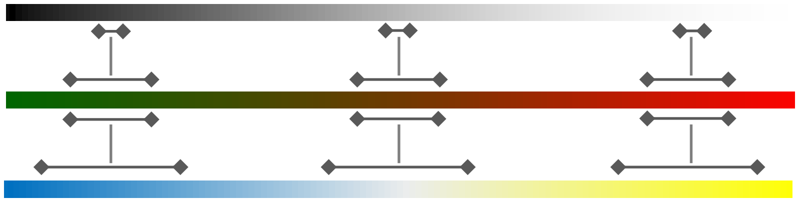
Models Converge Quickly



Verifying our Adapted Model

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

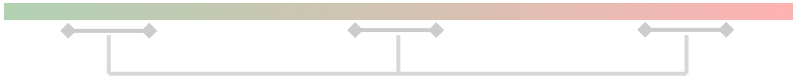
Properties of CIELAB



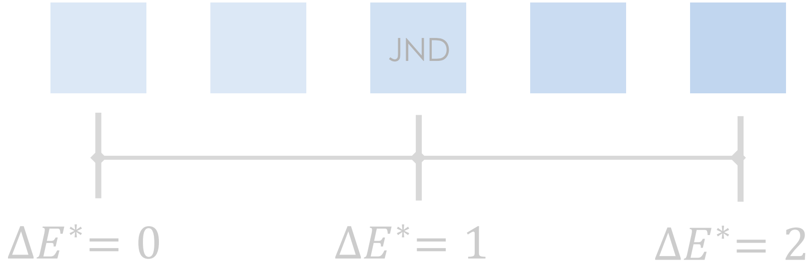
A1: Axes are orthogonal

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

A2: Difference is Euclidean

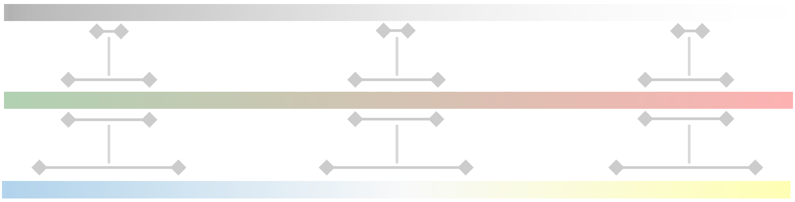


A3: Axes are uniform



A4: One unit is one JND

Properties of CIELAB



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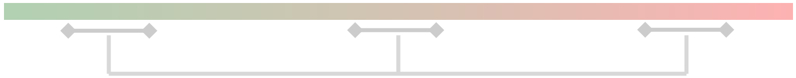

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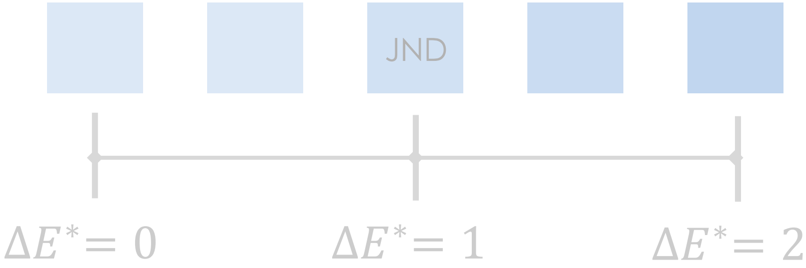

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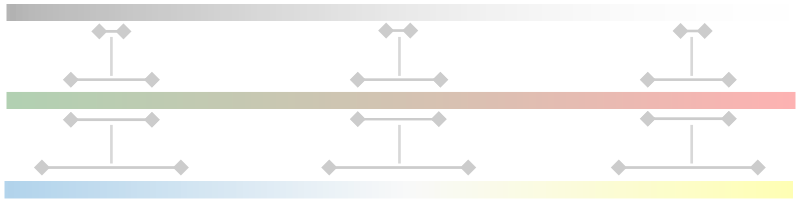

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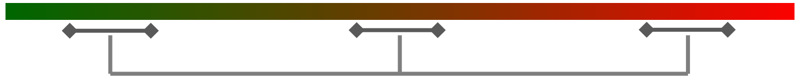

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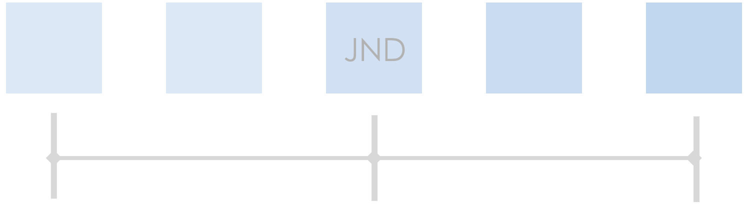

$\Delta E^* = 0$ $\Delta E^* = 1$ $\Delta E^* = 2$

A4: One unit is one JND