# A New Metric for Lighting Preference

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Imagination at work.

# Introduction

Spectrally enhanced lighting products are often preferred by consumers

Existing color quality metrics struggle to quantify consumer preference

<u>Goal</u>

Develop a color metric that accurately **quantifies and predicts consumer preference**, with capability as a design tool for product development in **preference applications**

# Preference Background

Two main preference drivers

- Color of Objects
- Color of White (source)

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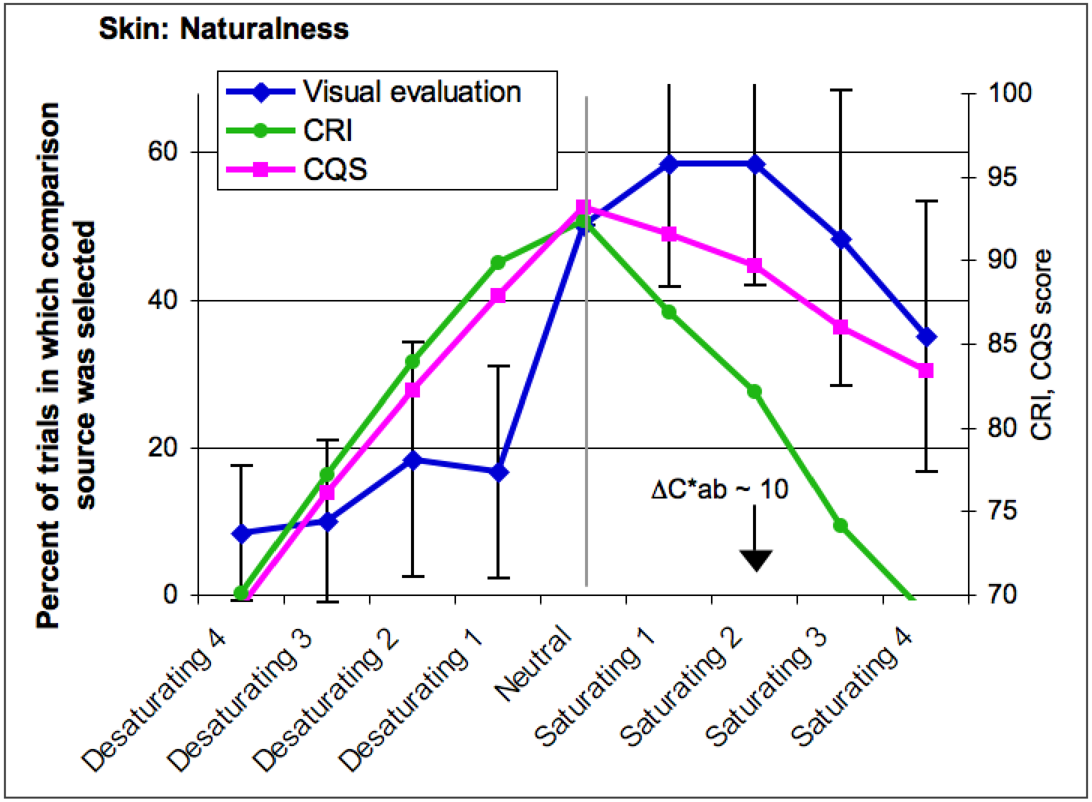
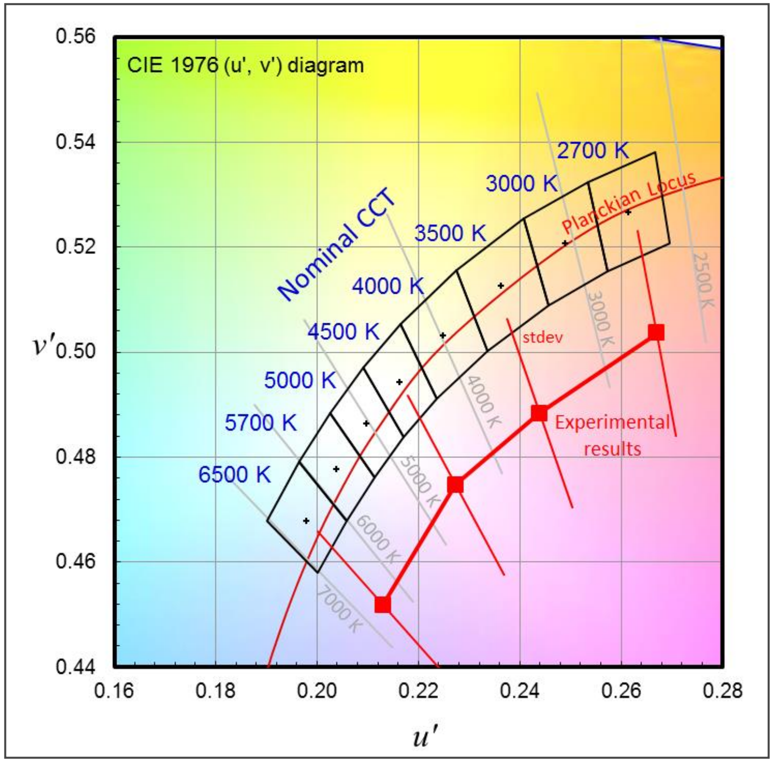



Ohno, Y. "Color Quality Design for Solid State Lighting," Presentation at LEDs 2012, Oct. 11-12, 2012.

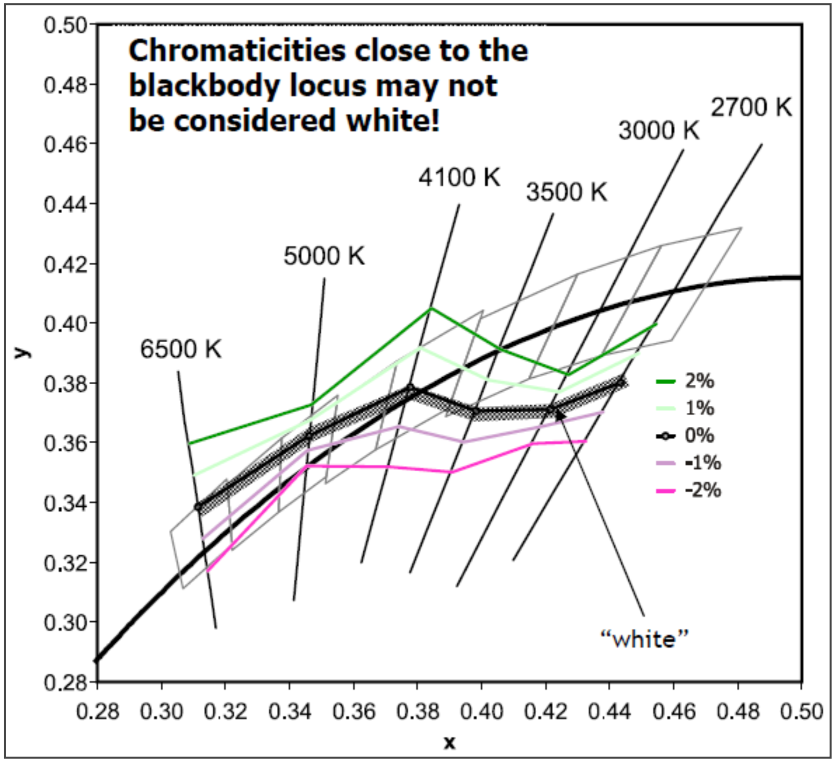
# Preference Background

## Two main preference drivers

- Color of Objects – Saturation generally preferred, to a limit
- Color of White (source) – Negative Duv preferred (warm CCTs)




Ohno, Y. and Fein, M. "Vision Experiment on White Light Chromaticity for Lighting," Presentation at CIE/USA-CNC/CIE Biennial Joint Meeting, Nov. 7-8, 2013.




Rea, M.S. and Freyssinier, J.P. "White lighting," Color Res. Appl. 38(2), 82-92 (2013)

# Categories of Existing Metrics

## Fidelity

- Examples: CRI ($R_a$), $R_9$, $Q_f$, $R_f$ (TM-30)
- Reference illuminant represents optimal color appearance
- Metrics quantify absolute difference from reference, regardless of better or worse quality

## Discrimination

- Examples: GAI, $Q_g$, $R_g$ (TM-30)
- Tend to favor higher CCTs and color points below Planckian locus
- Metrics quantify total color gamut and optimize to extreme levels of saturation and hue distortion

## Preference

- Examples: $R_f$, CPI, MCRI
- Utilize "ideal" configurations of test color samples at saturated levels
- Do not factor in "whiteness", or color point, of test source

# Lighting Preference Index (LPI)

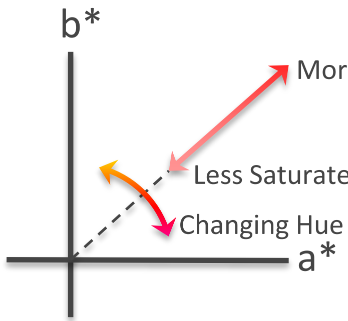
## Preference Drivers

- Color appearance - enhanced saturation, minimal hue distortion
- "Whiteness" of source - color points near "white" line (Duv ~ -0.010)

$$LPI = f(ColorApp, Whiteness)$$

## Test Color Samples

- Library of 1600 Munsell colors, statistical approach*
  - Hue – 10 categories, with 4 subcategories in each (40 total)
  - Chroma – Ranging from 0 to 16
  - Value – Ranging from 0 to 10
- Color rendition vectors (CRVs) generated in CIELAB color space

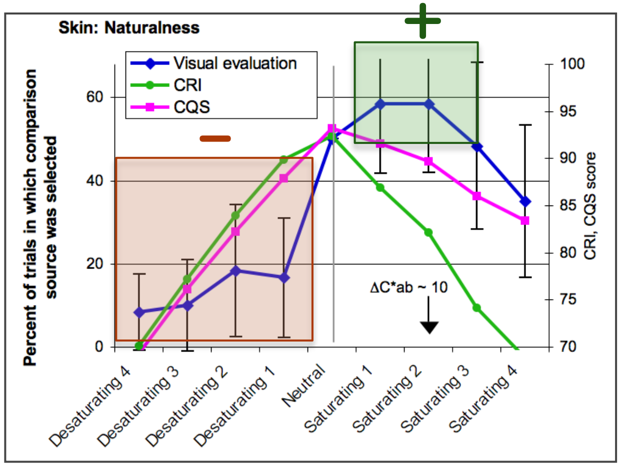



* A. Zukauskas, R. Vaicekauskas, F. Ivanauskas, H. Vaitkevicius, P. Vitta, and M.S. Shur, "Statistical approach to color quality of solid-state lamps," IEEE J. Sel. Top. Quantum Electron. 15(6), 1753 (2009).

# Lighting Preference Index (LPI)

## Color Appearance

- Two values calculated from CRVs
- *Net Saturation Value (NSV)*
  - Percent difference between improved saturation and decreased saturation
- *Hue Distortion Value (HDV)*
  - Weighted average of test colors changing hue
- Relative weighting based on observer preference response

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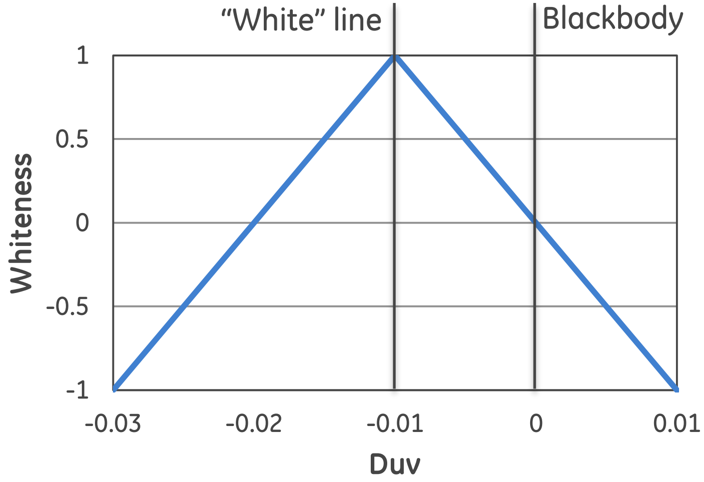
$$ColorApp = \frac{(NSV - HDV/2.5)}{50}$$

# Lighting Preference Index (LPI)

## Whiteness

- Function of Duv
- Targets "white" line at Duv = -0.010 for warm CCTs (2700-3000K)
- Scaled for blackbody = 0 and "white" line = 1




$$Whiteness = 1 - 100\sqrt{(Duv + 0.01)^2}$$

# Lighting Preference Index (LPI)

Relative weighting of components determined empirically using color tunable sources

$$LPI \, \alpha \, 0.38 * Whiteness + 0.62 \ * ColorApp$$

Reference illuminant set to 100 (Whiteness = 0, ColorApp = 0)

Magnitude scaled similar to CRI

- Neodymium Incandescent: CRI ~80, LPI ~120

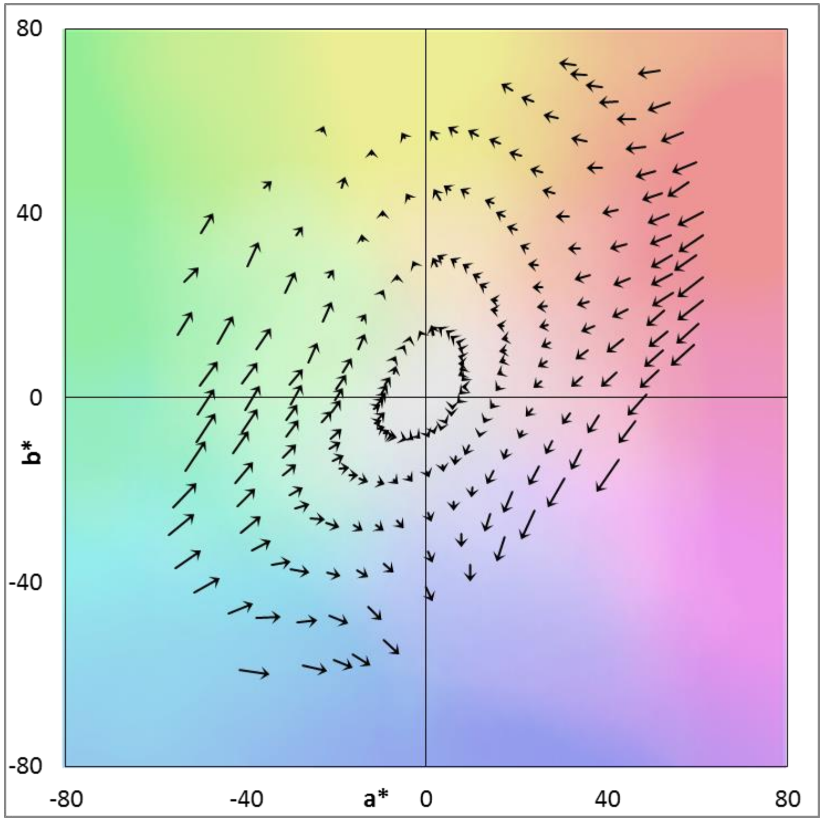
$$LPI = 100 + 50 * (0.38 * Whiteness + 0.62 \ * ColorApp)$$

$$LPI = 100 + \boxed{19 * \left(1 - 100\sqrt{(Duv + 0.01)^2}\right)} + \boxed{0.62 \ * \left(NSV - \frac{HDV}{2.5}\right)}$$

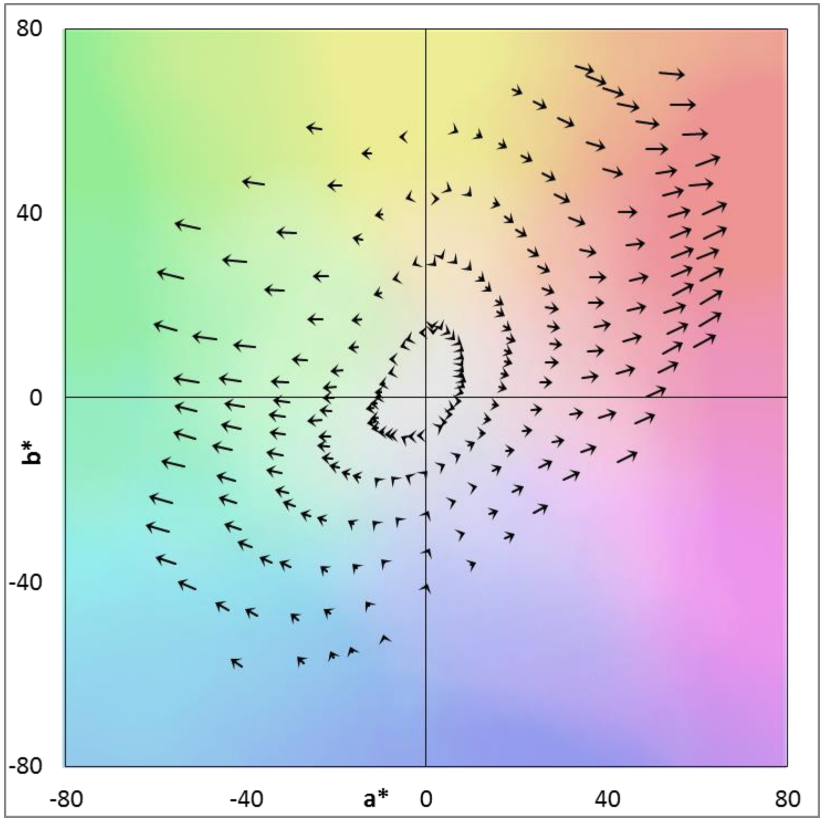
Whiteness

Color Appearance

# Vector Plot of CRVs




Standard LED lamp
80 CRI, 89 LPI




Neodymium incandescent lamp
80 CRI, 122 LPI

# Observer Testing

Preference study with 12 observers

Head-to-head matchups between 14 illuminants

- Incandescent, CFL, LED sources – 2700K, Duv -0.007 to +0.003
- Overall preference rated on 0-3 scale
  (0 - no, 1 - slight, 2 – medium, 3 - strong preference)

Preference score calculated for each test source

- Average of all head-to-head matchups over all observers
- Range from -3 (strongly not preferred) to +3 (strongly preferred)
- Quantifies and ranks preference response of all 14 sources

# Observer Testing

| Pearson Correlation Coefficients (* p-value less than 0.01) | | | | | |
|---|---|---|---|---|---|
| Fidelity Metrics | | Discrimination Metrics | | Preference Metrics | |
| CRI ($R_a$) | -0.59 | GAI | 0.95* | $R_f$ (flattery) | -0.38 |
| CQS ($Q_a$) | -0.42 | $Q_g$ | 0.84* | CPI | 0.66 |
| $R_f$ (TM-30) | -0.39 | $R_g$ (TM-30) | 0.80* | LPI | 0.95* |

Strong correlations with LPI and the discrimination metrics

Discrimination metrics and preference response expected to diverge with broader test source selection

- Additional testing ongoing with over-saturated spectra and color points further below Planckian locus

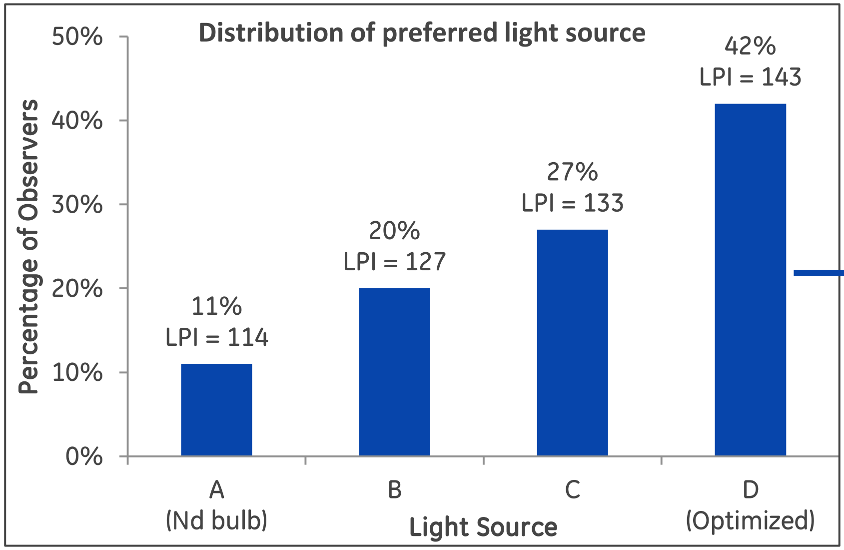
LPI appears as strong indicator of consumer preference

# Design Capability

LPI used to evaluate and optimize potential design parameters

Validation Study

- Four LED sources at 2700K with enhanced levels of LPI
- Observer study with 86 participants



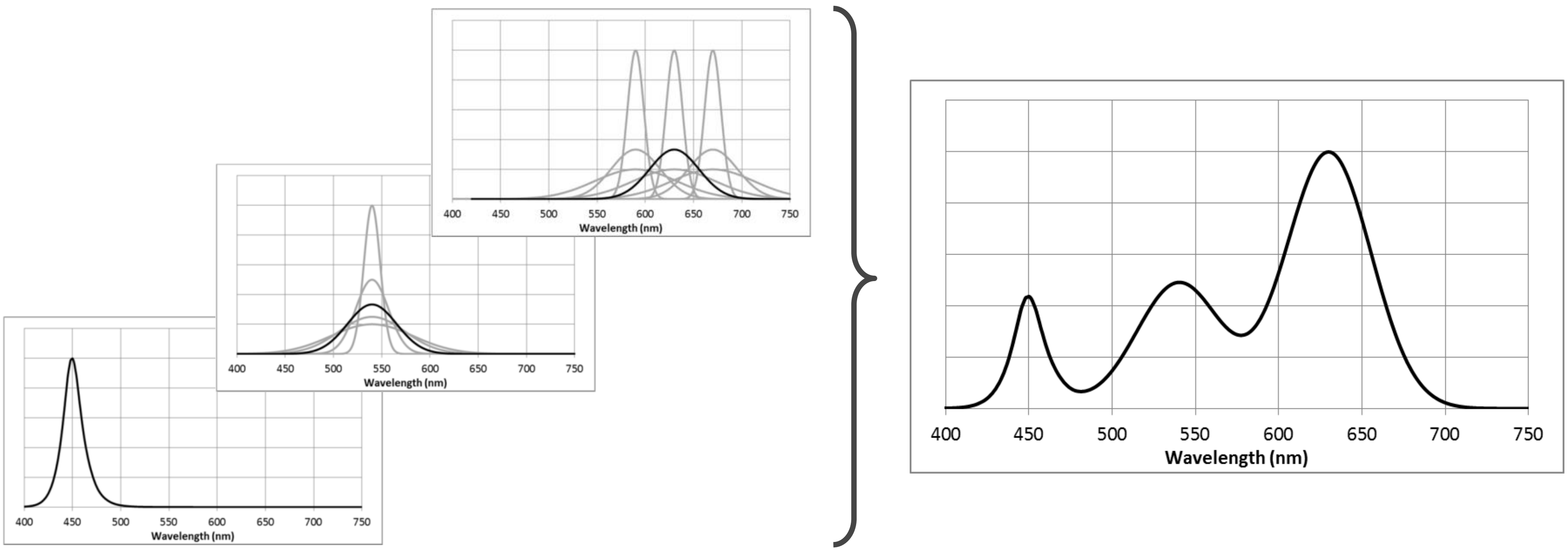

LPI = 143
CRI = 62

LPI allows predictive analysis and use as optimizable design tool

# Spectral Modeling

## LED spectral modeling exercise

- Three component spectrum: blue LED + green Gaussian + red Gaussian
- Peak and FWHM varied to simulate LED and phosphor emissions
- 4,050 spectra generated for fixed color point (metamers)



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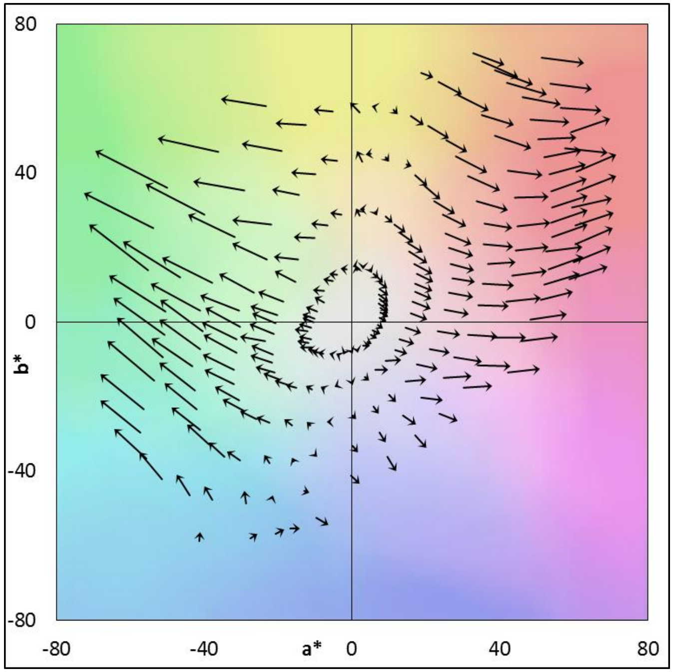
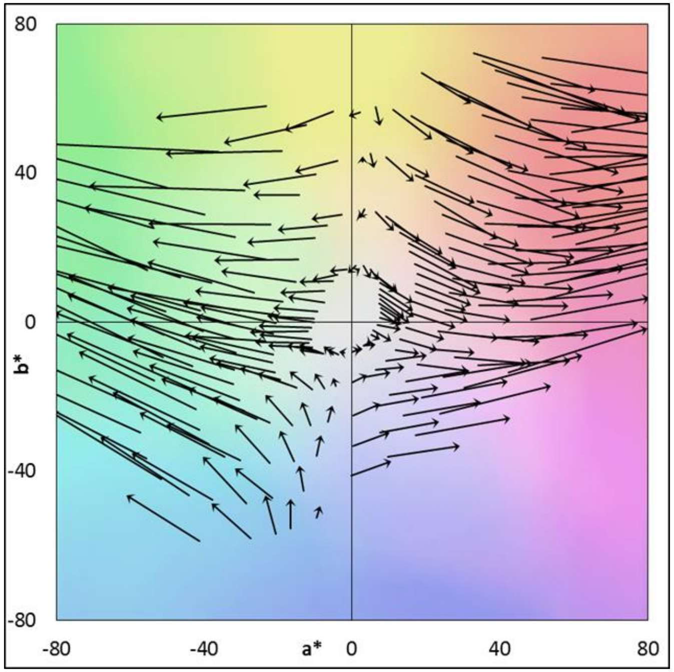


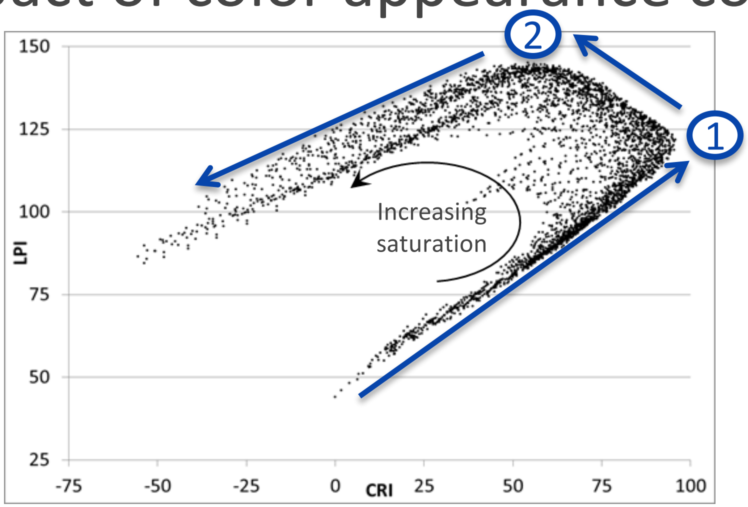

Optimized to LPI
54 CRI, 87 GAI, 145 LPI

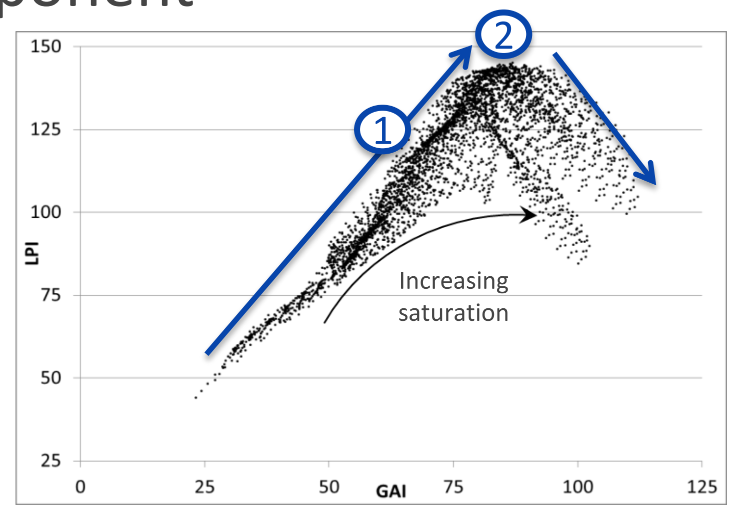



Optimized to GAI
-36 CRI, 112 GAI, 105 LPI

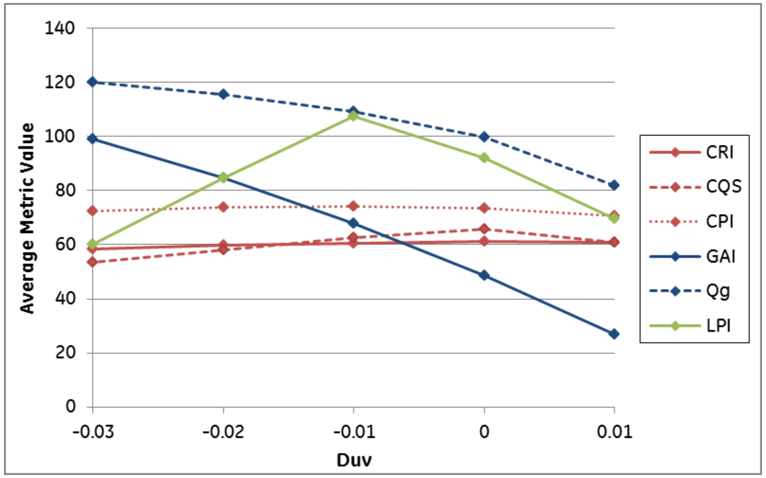
# Spectral Modeling

## Impact of color appearance component




## Impact of whiteness component



# Summary/Next Steps

LPI combines color appearance and whiteness of test source into a single preference metric

Preliminary testing shows favorable results for the use of LPI as an indicator, and predictor, of consumer preference

Additional testing ongoing to refine and validate metric

- Over-saturated spectra
- Color points beyond “white” line
- Color temperatures higher than 2700-3000K

# Thank You!

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