www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

Class A Color Classification for Light Sources Used in General Illumination

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Jean Paul Freyssinier

October 2012

Lighting Research Center

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Introduction

- **Color rendering** and the **color of illumination** are two key factors that support architectural lighting (e.g., retail lighting).
- However, presently accepted metrics used to describe color properties (CRI and CCT) often are not perfectly predictive of people's assessments of illumination from a light source.

photos.com

Amerlux

Amerlux

www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

Color Rendering of Illumination

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Basic issues

- CRI is used almost exclusively for color rendering

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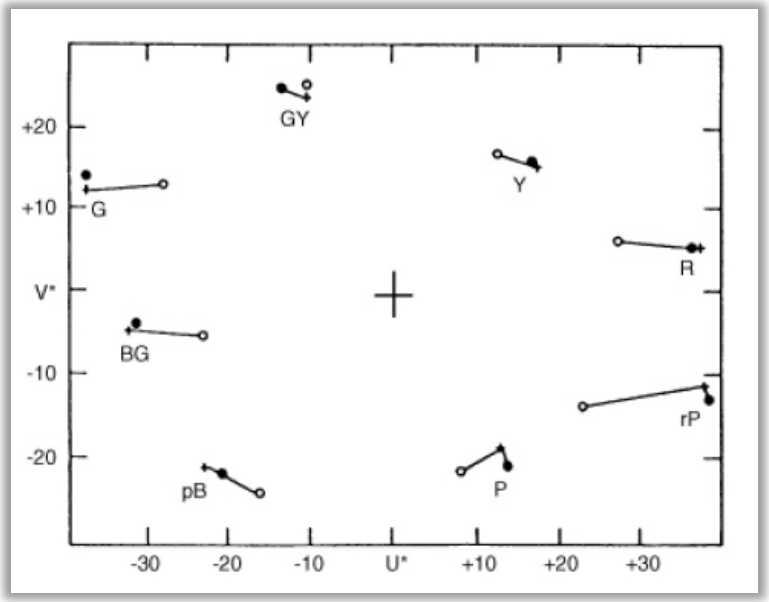
Table 1. Most useful light source color characteristics.

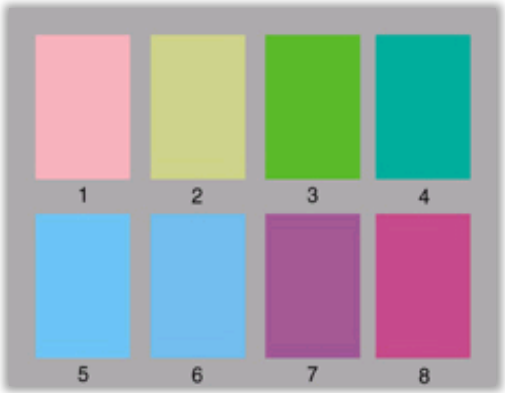
Characteristic	Average Usefulness Rating	Standard Deviation	Number of Responses
Color Rendering Index (CRI)	3.5	0.7	237
Correlated Color Temperature (CCT)	3.2	1.0	233
Color Stability	3.2	1.0	232
Lamp Type	3.1	1.0	235
Color Consistency	3.1	1.0	228
Spectral Power Distribution (SPD)	2.4	1.2	226
Full-Spectrum Index (FSI)	2.0	1.3	204
Brand Name	1.9	1.2	226
Gamut Area	1.5	1.2	189

(Rating Key: 0 = Not useful; 4 = Very useful)

Color rendering index (CRI)

- Measure of the degree of color shift objects undergo when illuminated by the light source as compared with the color of those same objects when illuminated by a reference source of comparable color temperature.





IESNA Lighting Handbook, 9th Ed. (2000)

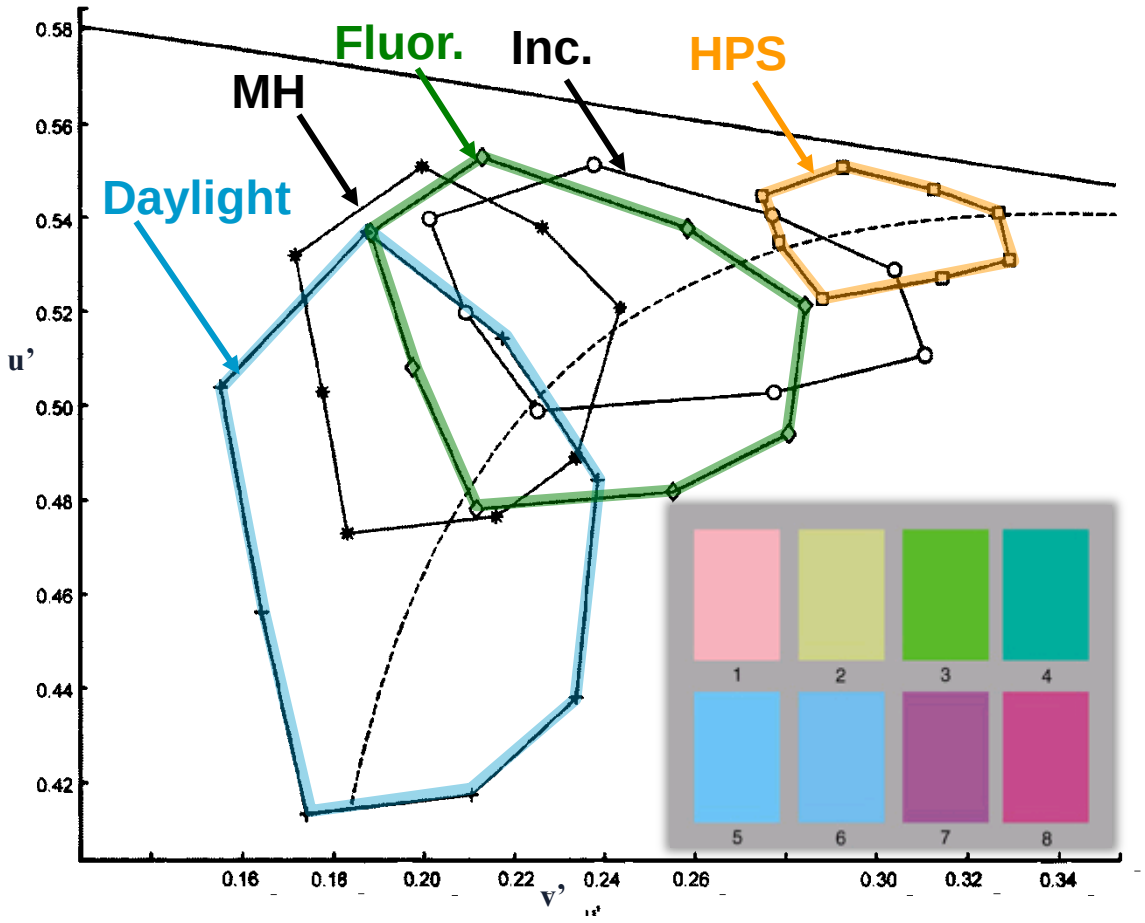
CRI = 90

CRI = 70

CRI = 50

Color gamut area

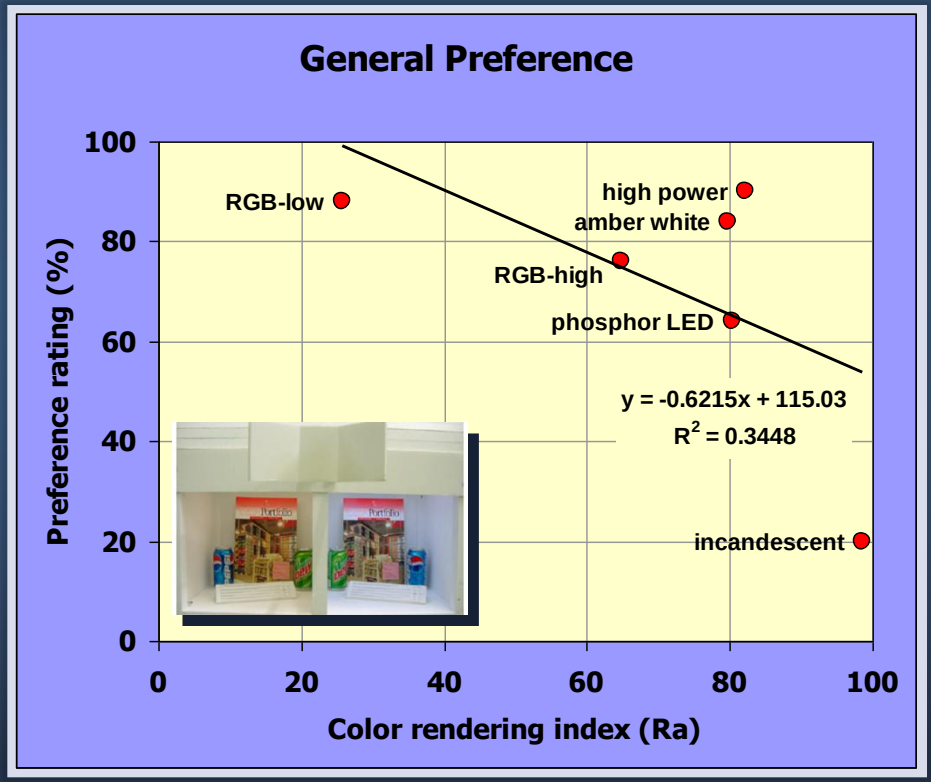
- In general, the larger the gamut area, the more saturated the color samples are and the easier it is to discriminate between them.

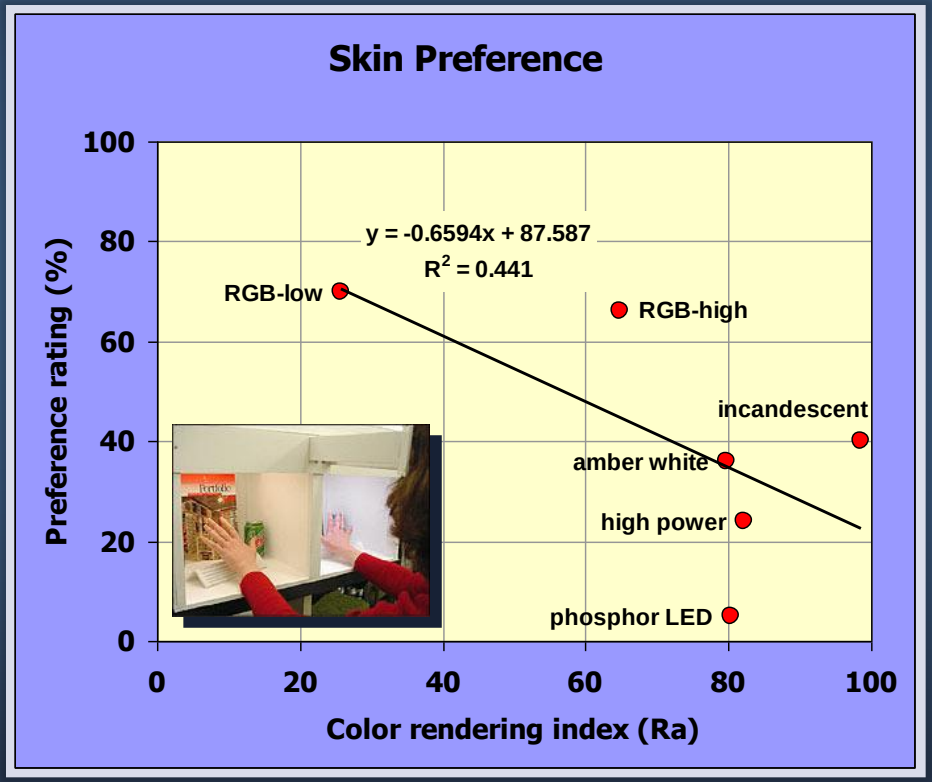


Adapted from ***Human Factors in Lighting*** **- 2nd Edition**
Boyce, P. R. 2003. London; New York: Taylor & Francis.

Basic issues

- Solid-state lighting is putting new demands on old metrics

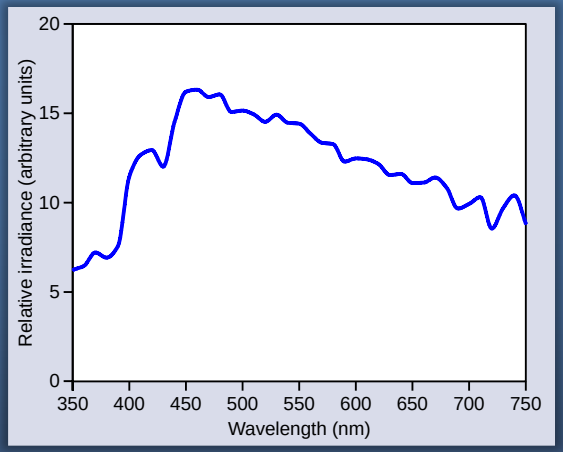




Color Rendering Properties of LED Light Sources
N. Narendran and L. Deng. 2002. *Solid State Lighting II: Proceedings of SPIE*

Basic issues

- Different dimensions of color rendering
  - Bouma (1948) suggested that daylight is the best source: naturalness, hue discrimination, color naming accuracy
  - Within CIE's TC1-69 committee, several concepts are used:
    - Fidelity
    - Colorfulness
    - Naturalness
    - Memory
    - Discrimination
    - Preference
    - Clarity
    - Vividness
    - …and over 10 more



Bouma, P.J. 1948. *Physical aspects of colour; an introduction to the scientific study of colour stimuli and colour sensations.* Eindhoven: Philips Gloeilampenfabrieken (Philips Industries) Technical and Scientific Literature Dept.

www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

Experimental Approach

- Objective evaluation
  - Farnsworth-Munsell 100 hue test
- Subjective evaluation
  - Restrict colors to red and blue
  - Restrict subjective responses to *vividness* and *naturalness*
  - Paired comparisons (sequential) for *vividness* and *naturalness*
- Compare different light levels
- Examine correlations of subjective and objective evaluations to CRI and GAI

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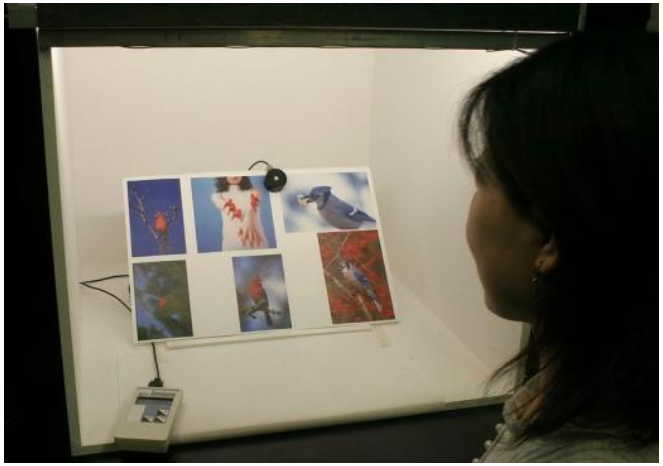
Experiment setup

- Farnsworth-Munsell 100-hue color vision test
- Collage of cardinal and blue jay pictures



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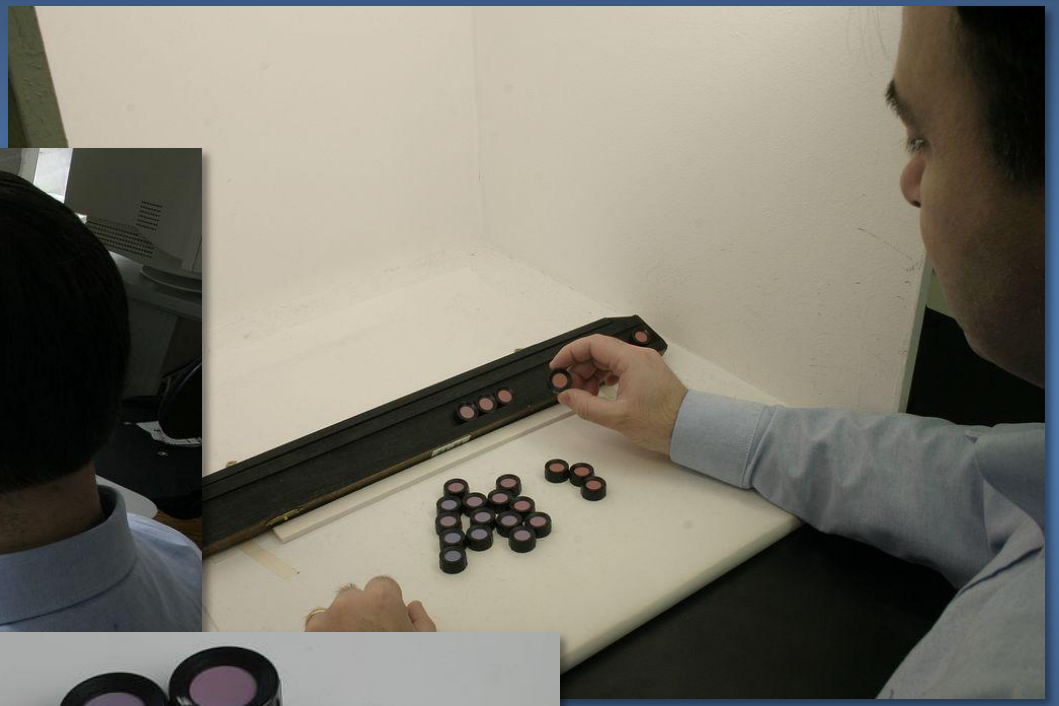
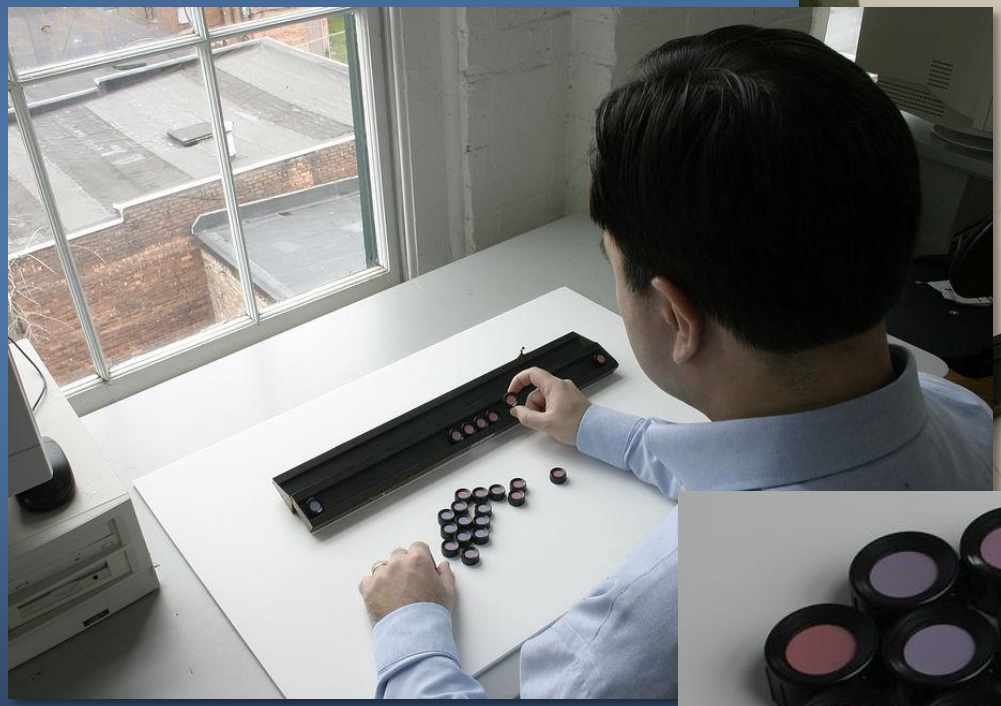
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

Experiment setup

Electric light source conditions



Daylight conditions



Apparatus

- Eight phosphor-based light sources
- Two light levels: 5 fc and 50 fc

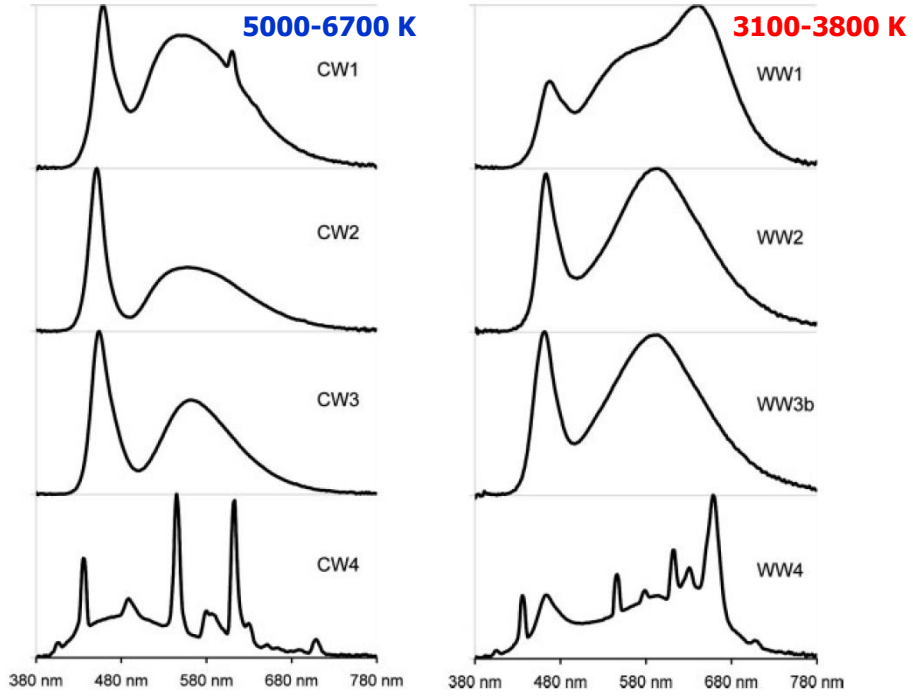


FIG. 2. Normalized spectral power distributions of the illuminants used in this study at 50 fc. Color characteristics or each illuminant are summarized in Table I.

Farnsworth-Munsell 100-hue test

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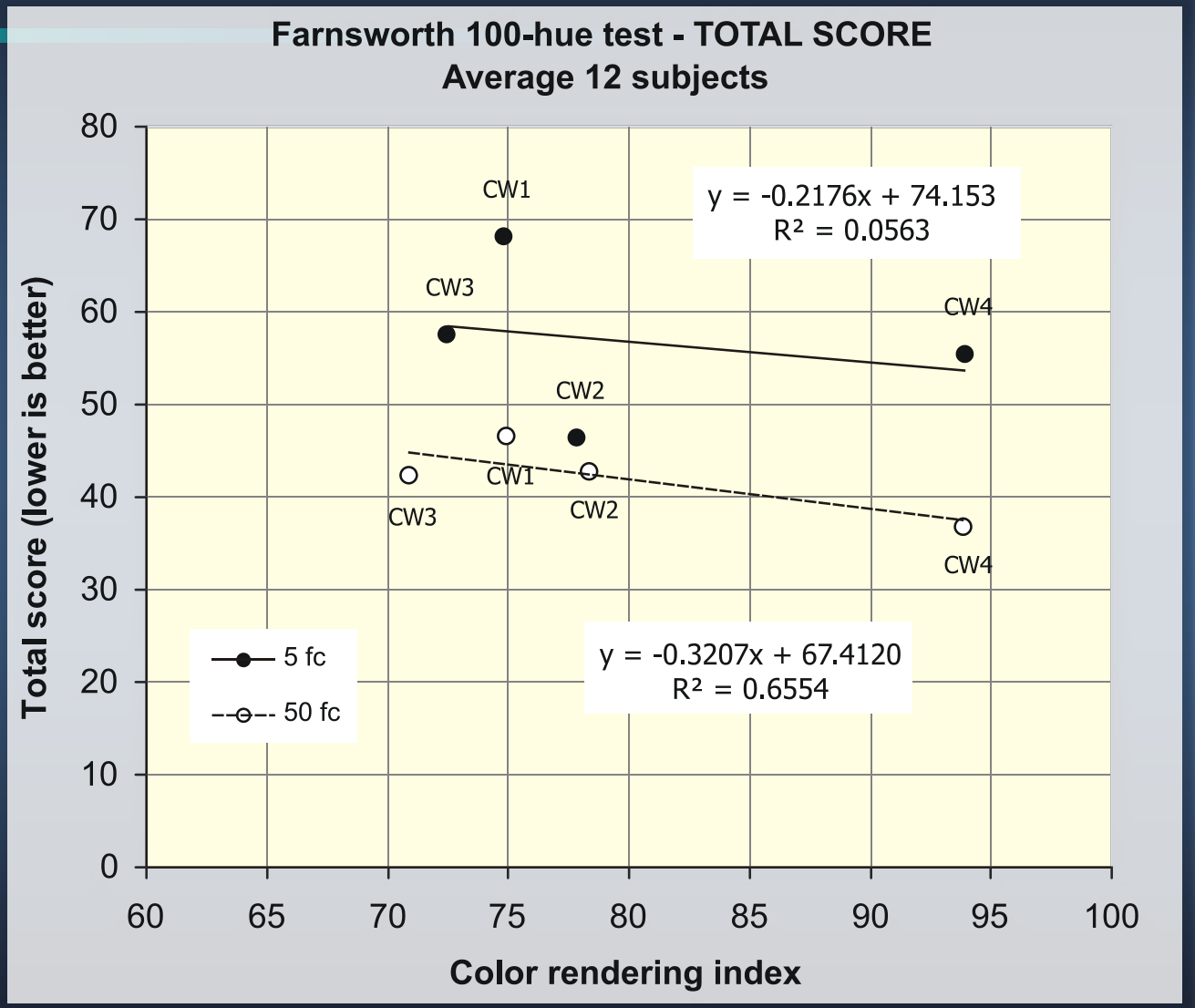
Farnsworth test results



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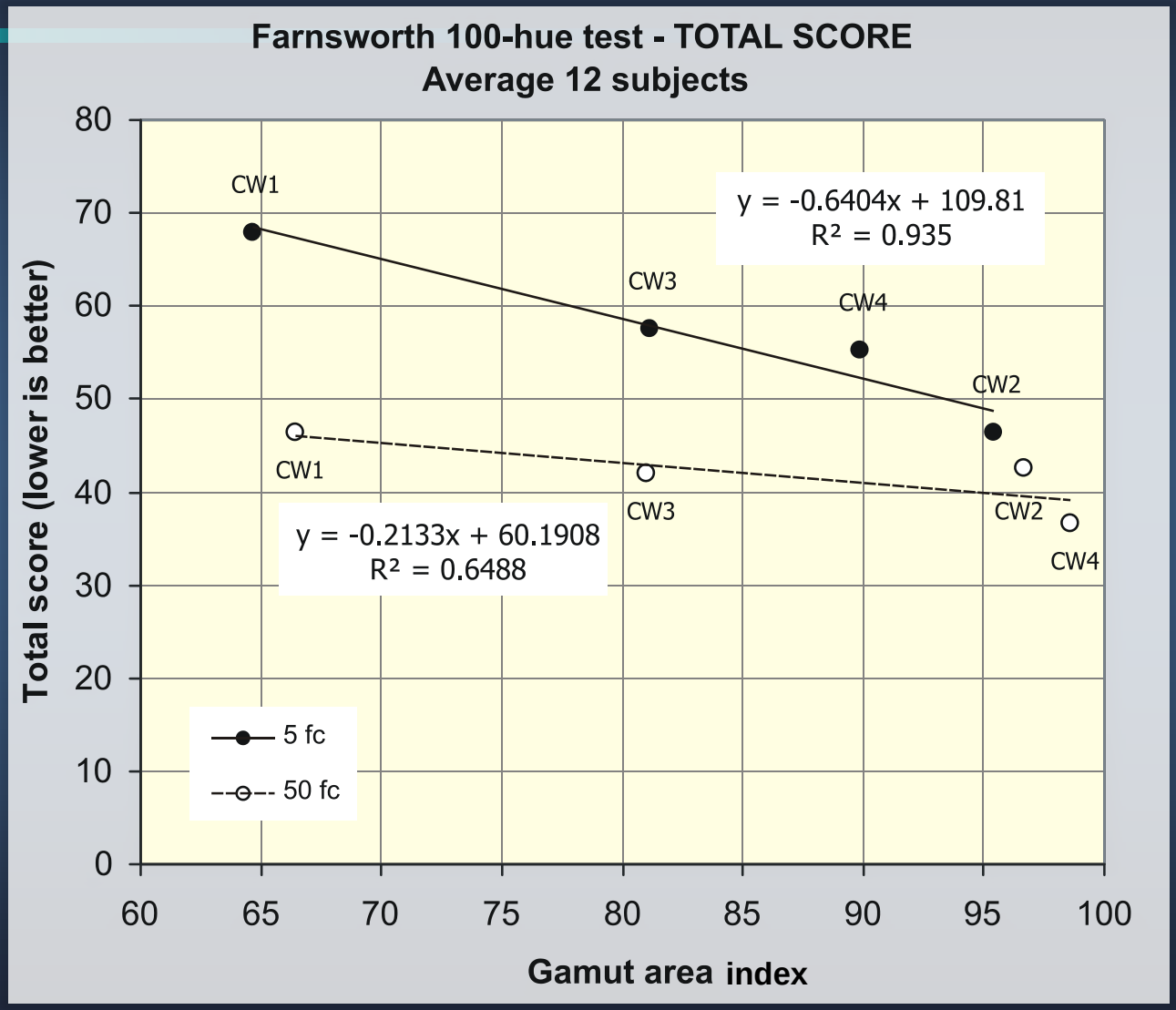

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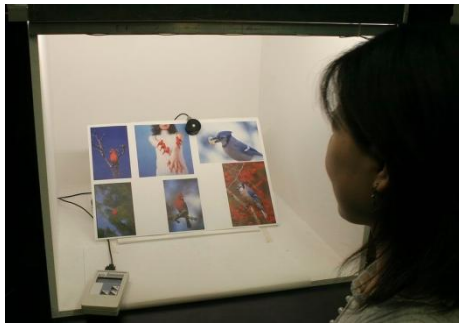
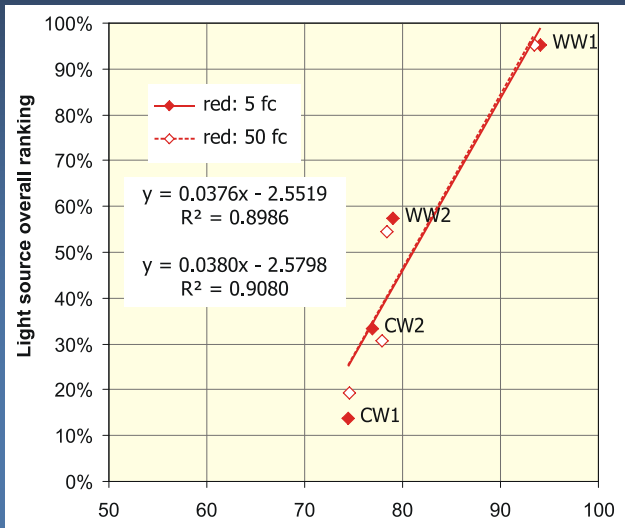
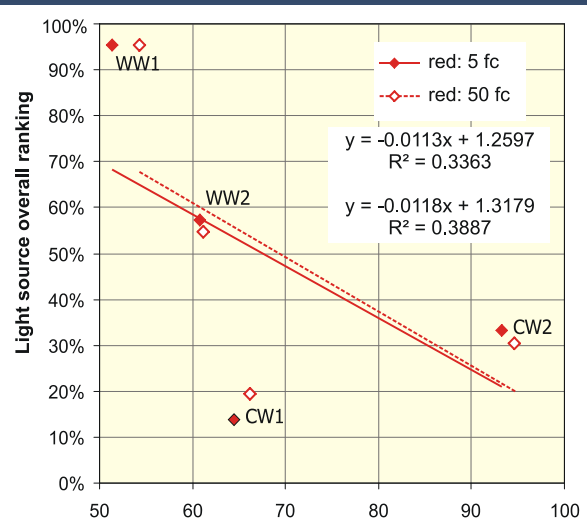
Paired comparisons mixed CCTs: Vividness



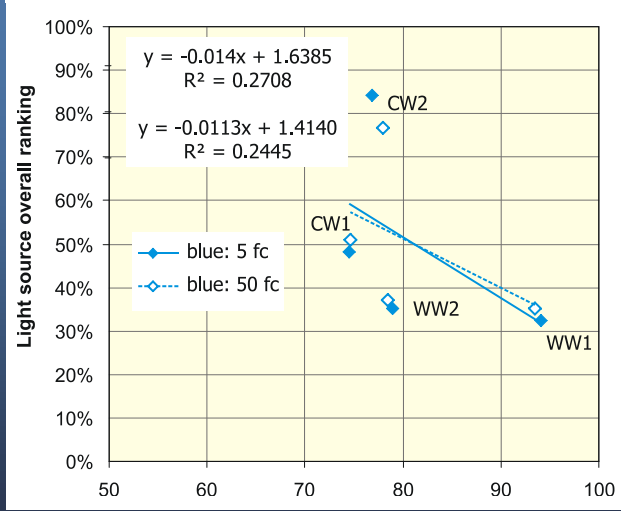
CRI GAI

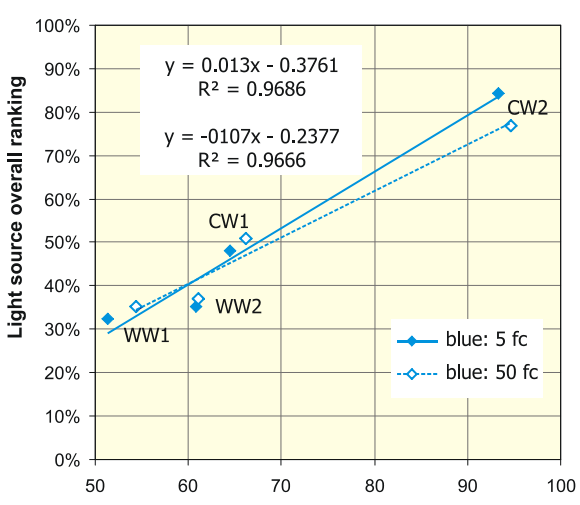
red





blue

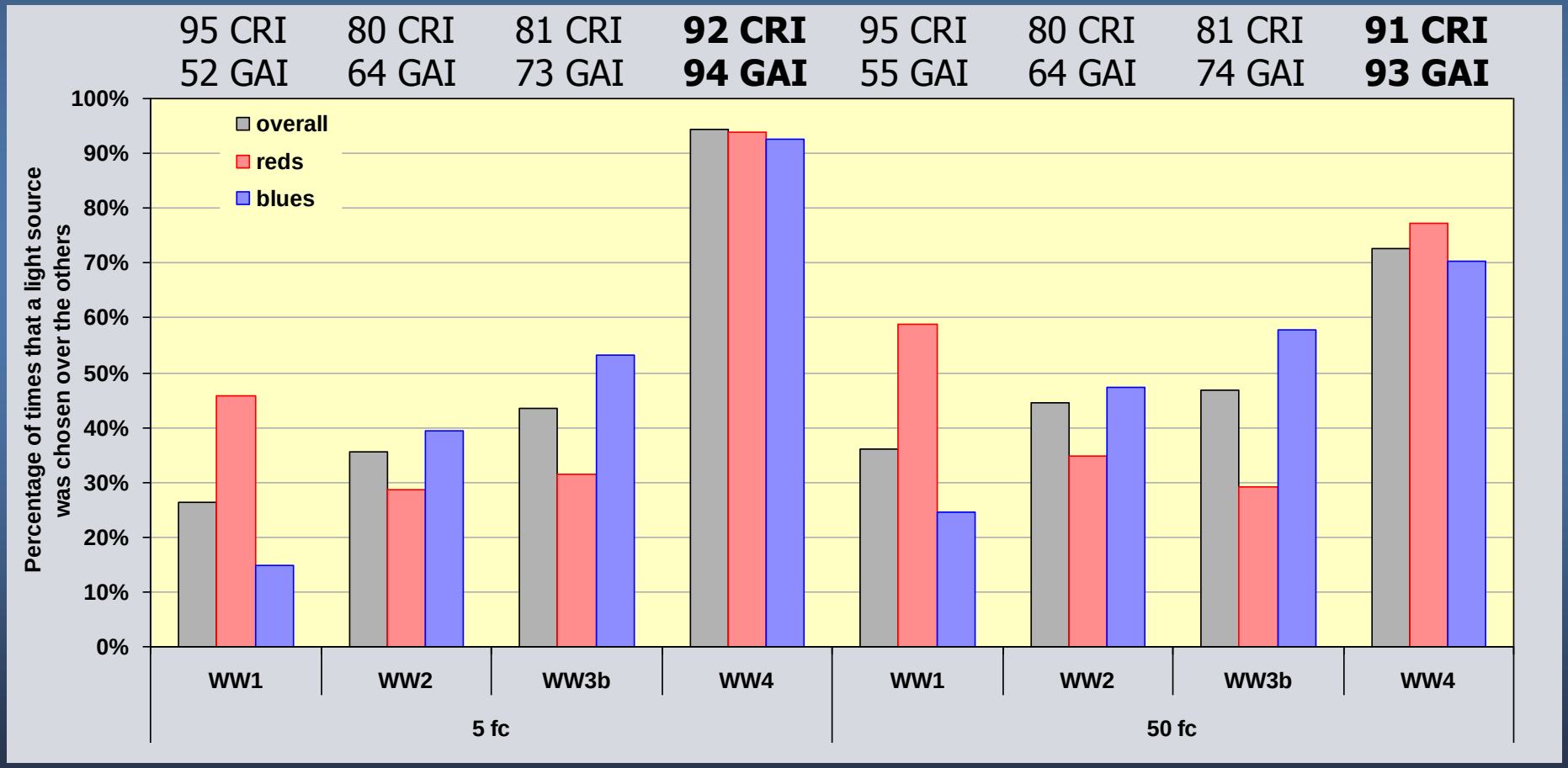




Rea MS, Freyssinier-Nova JP. Color rendering: A tale of two metrics. *Color Res Appl* 2008; 33:192-203

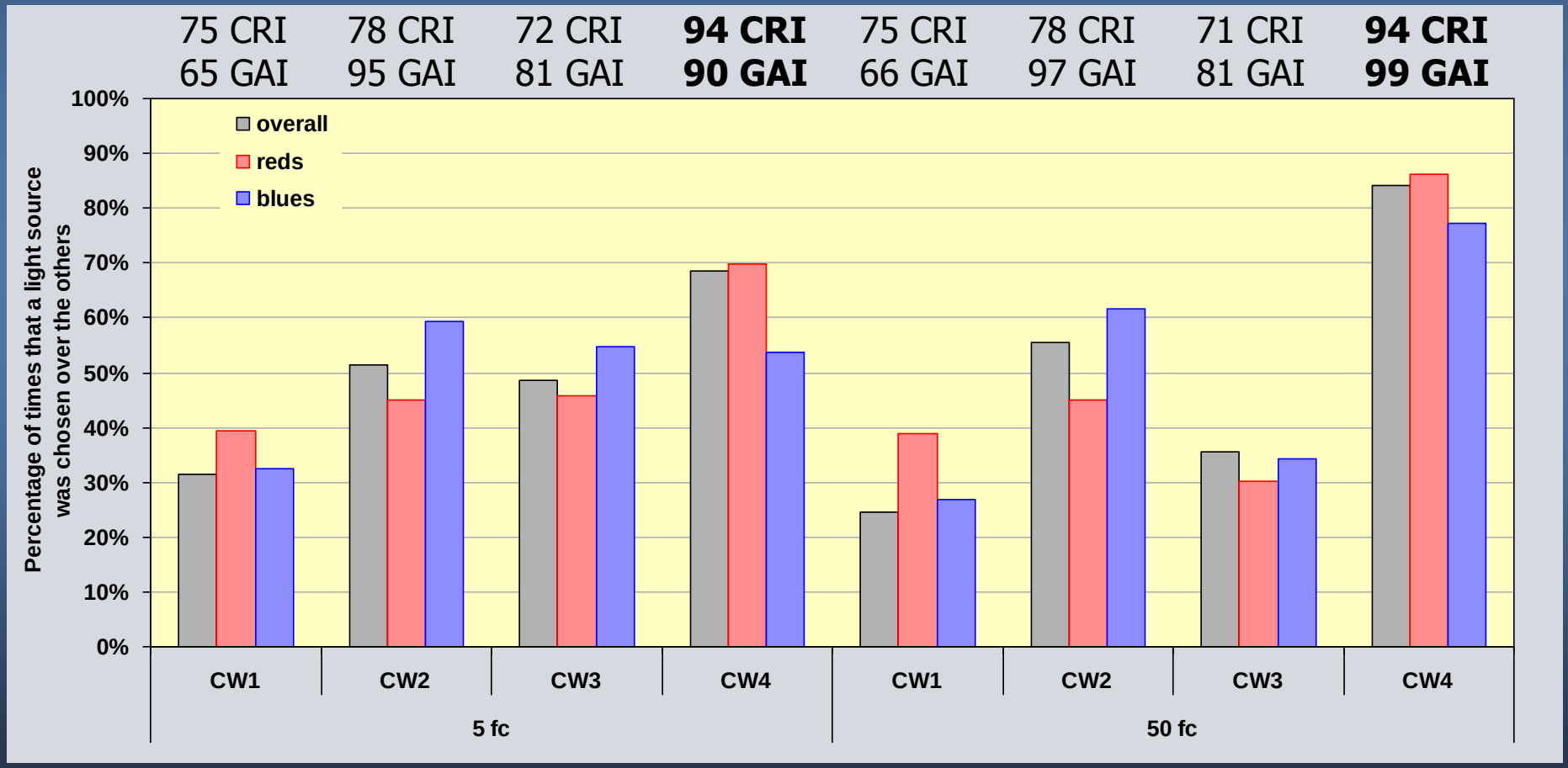
Paired comparisons: Vividness

- Warm CCTs (3100-3800 K)



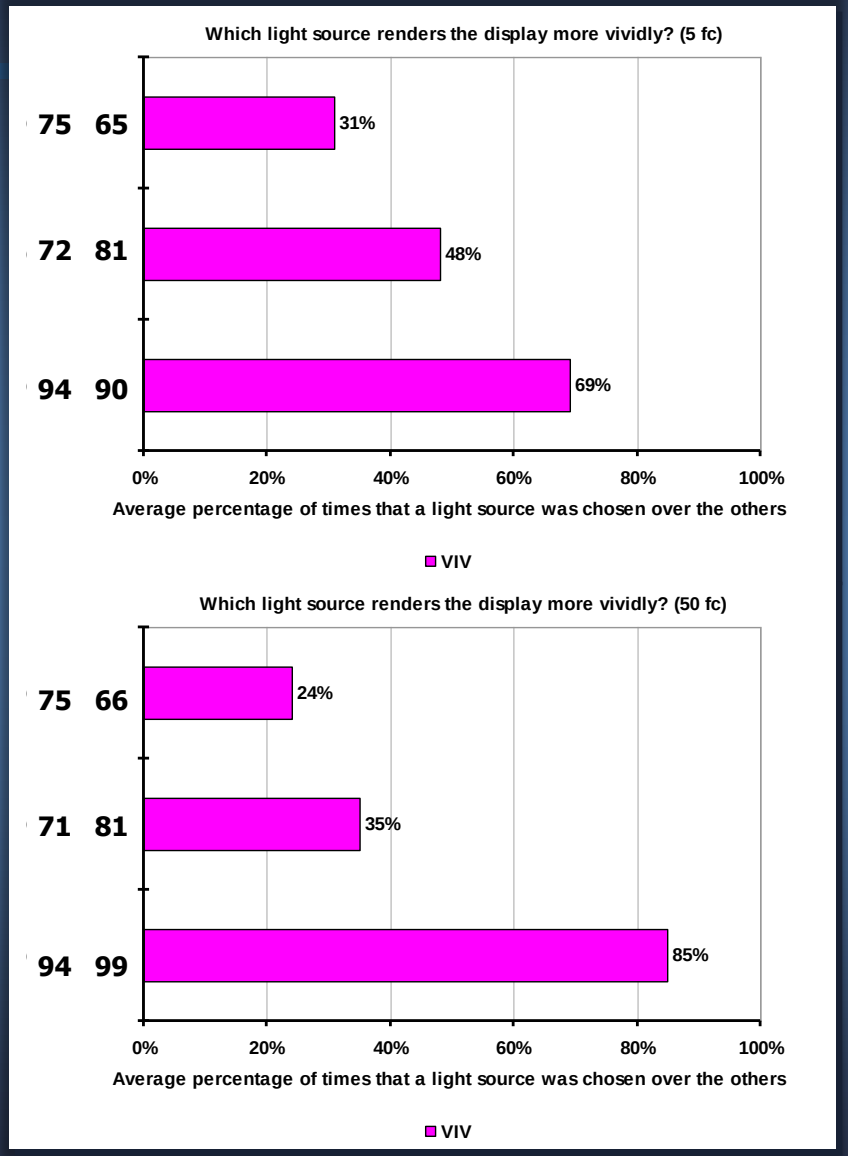
Paired comparisons: Vividness

- Cool CCTs (5000-6700 K)



Paired comparisons: Vividness

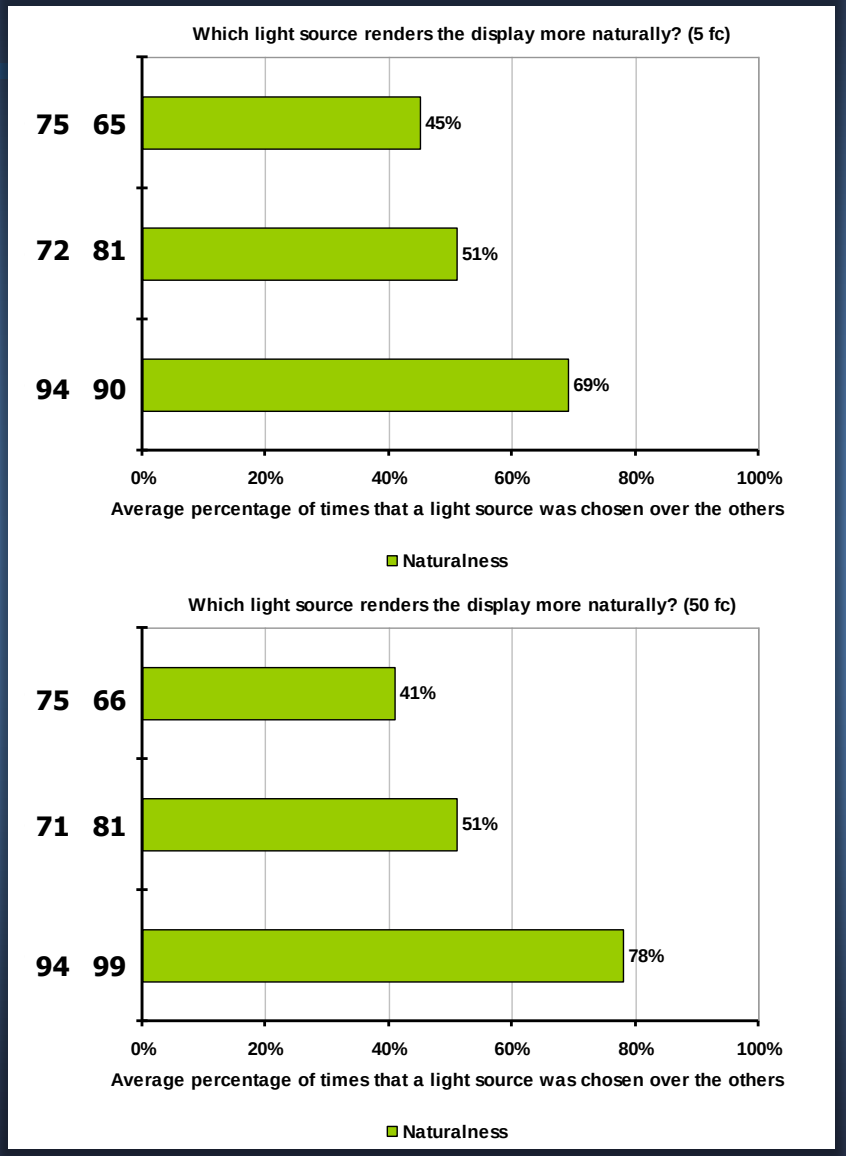
- Cool CCTs (5000-6400 K)
- Which light source, the first or the second, renders the display **more vividly**?
- 5 fc and 50 fc



Rea, M. S. and Freyssinier-Nova, J. P. (2008), Color rendering: A tale of two metrics. Color Research & Application, 33: 192–202. doi: 10.1002/col.20399

Paired comparisons: Naturalness

- Cool CCTs (5000-6400 K)
- Which light source, the first or the second, renders the display **more naturally**?
- 5 fc and 50 fc



Rea, M. S. and Freyssinier-Nova, J. P. (2008), Color rendering: A tale of two metrics. Color Research & Application, 33: 192–202. doi: 10.1002/col.20399

www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

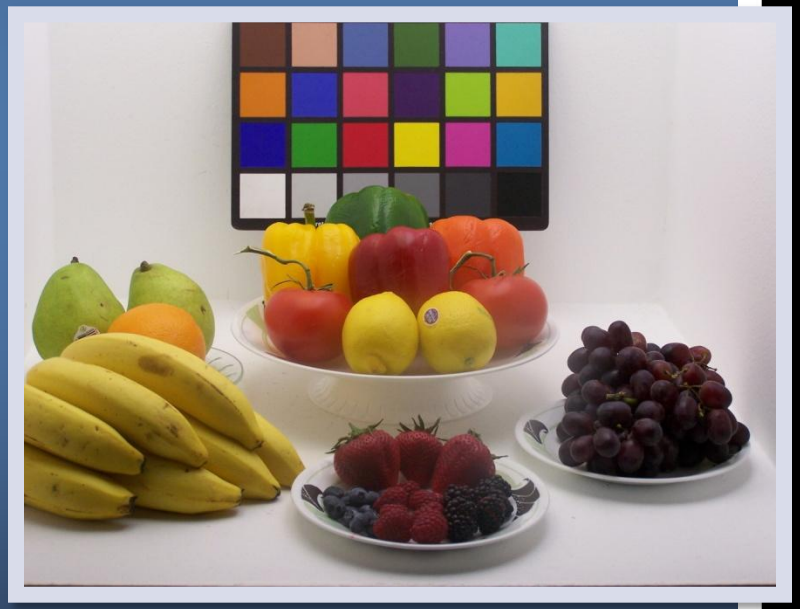
Experimental approach: A priori test of two-metric hypothesis

- Test directly the hypothesis that CRI and GAI complement each other
  - High CRI and high GAI will be preferred
- Subjective evaluation
  - Multicolor scene
  - Subjective responses to vividness, naturalness, and overall acceptability
  - Asked subjects to rank the hues that influenced their decisions the most
- Evaluation of one source at a time

www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

Apparatus

- Display of fresh fruits and vegetables
- Color chart



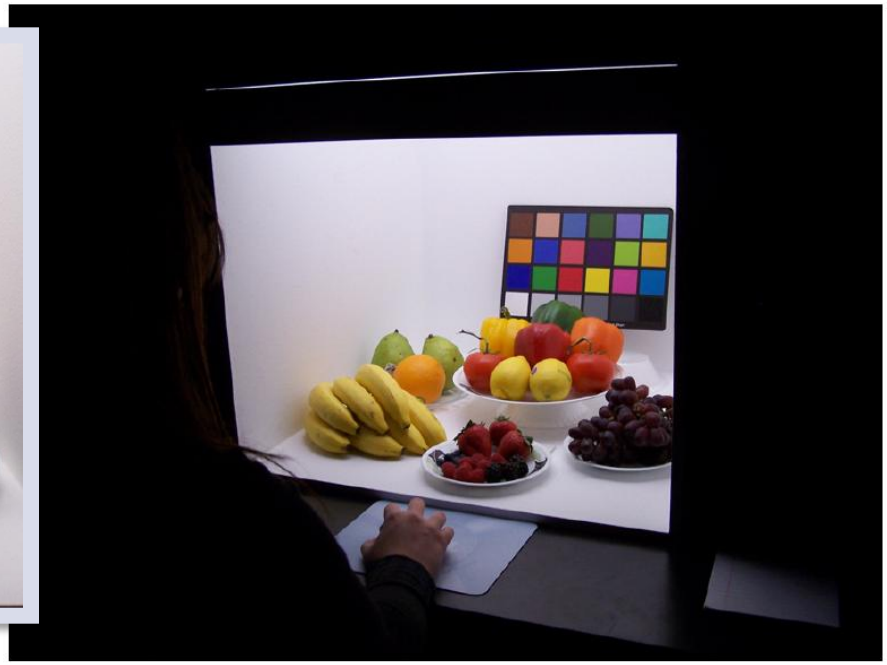
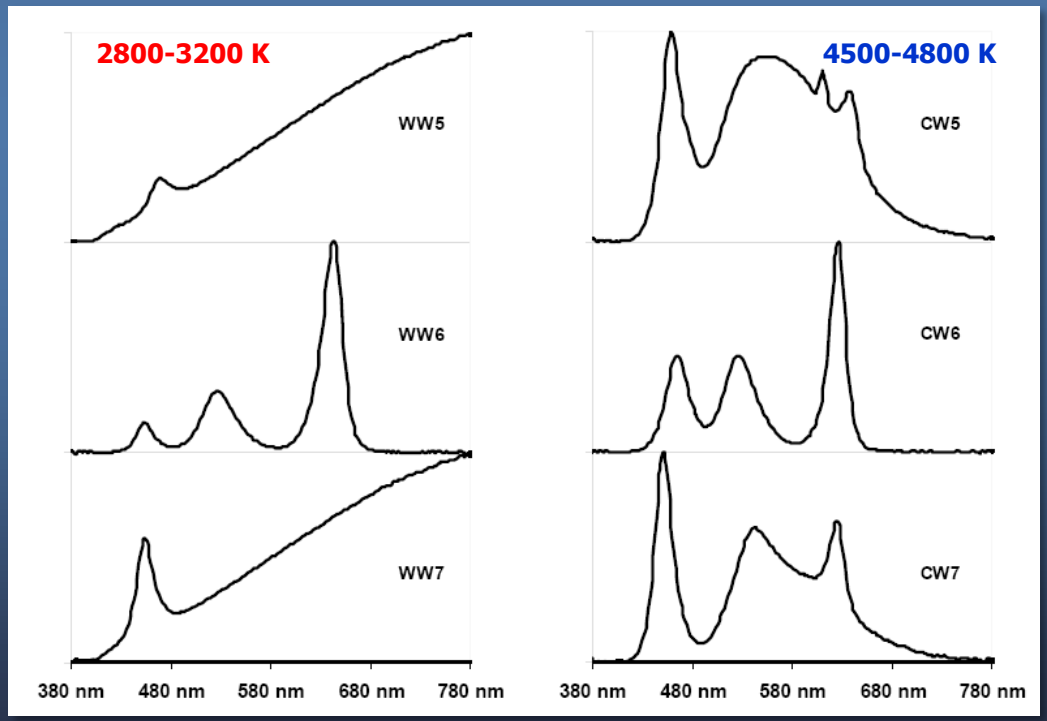
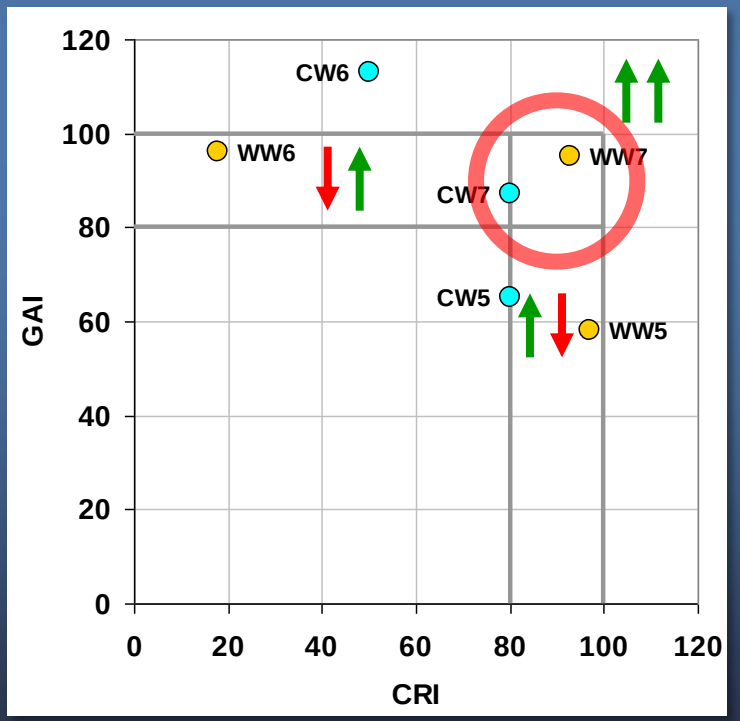


Figure 1. View of the experimental apparatus.

Apparatus

- Six light sources: combination of incandescent, phosphor and colored LEDs
- One light level: 355 lx horizontal illuminance



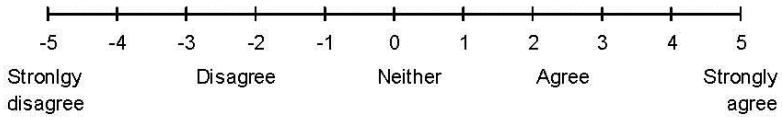


Task

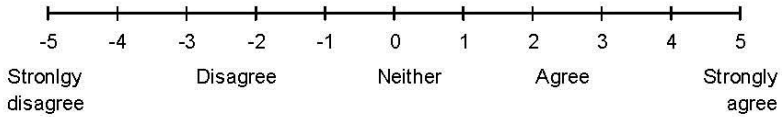
- Eighteen volunteers who had participated in previous color rendering studies answered four questions per light source

Instructions to observers:
Imagine that you are a grocer who wants to display fresh fruits and vegetables. As such you want to be sure that all the objects in the display appear vivid and look natural. Given that each source can enhance or mute a given color, you must pick the light source that renders all the fruits and vegetables well without making them dull or unnatural. A collection of fruits, vegetables and a color chart will be displayed sequentially under different "warm" and "cool" sources. Look at the display and then indicate using the two scales your assessment of the color rendering properties of the source for naturalness and vividness.

Overall, this light source makes this scene look NATURAL



Overall, this light source makes this scene look VIVID



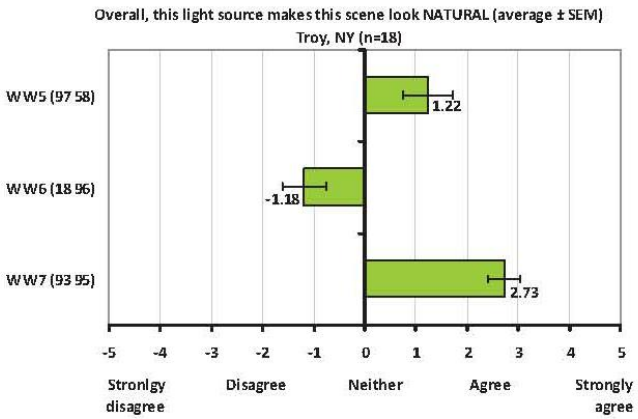
Next, please answer the question Is this light source acceptable, yes or no?

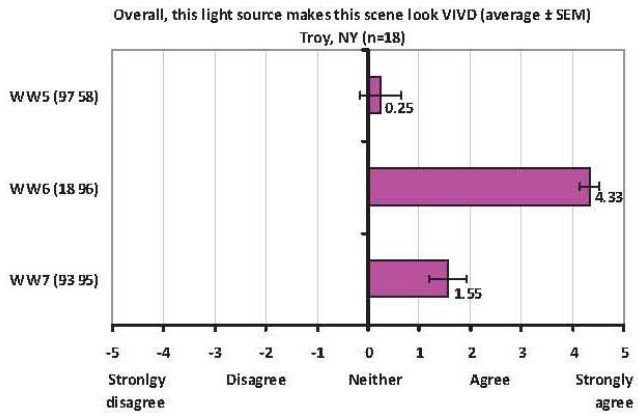
Finally, rank the three hues from the list that influenced you the most in forming your opinion about the light source.

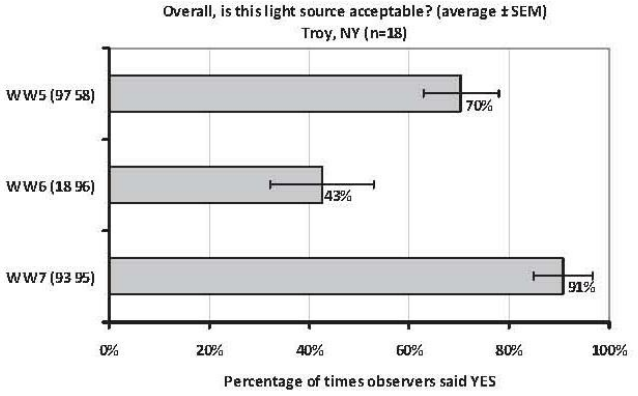
Red Orange Yellow Chartreuse Green Cyan Blue Purple

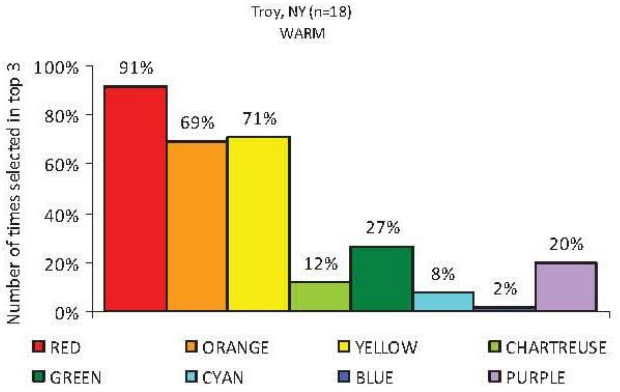
Results

LRC Warm





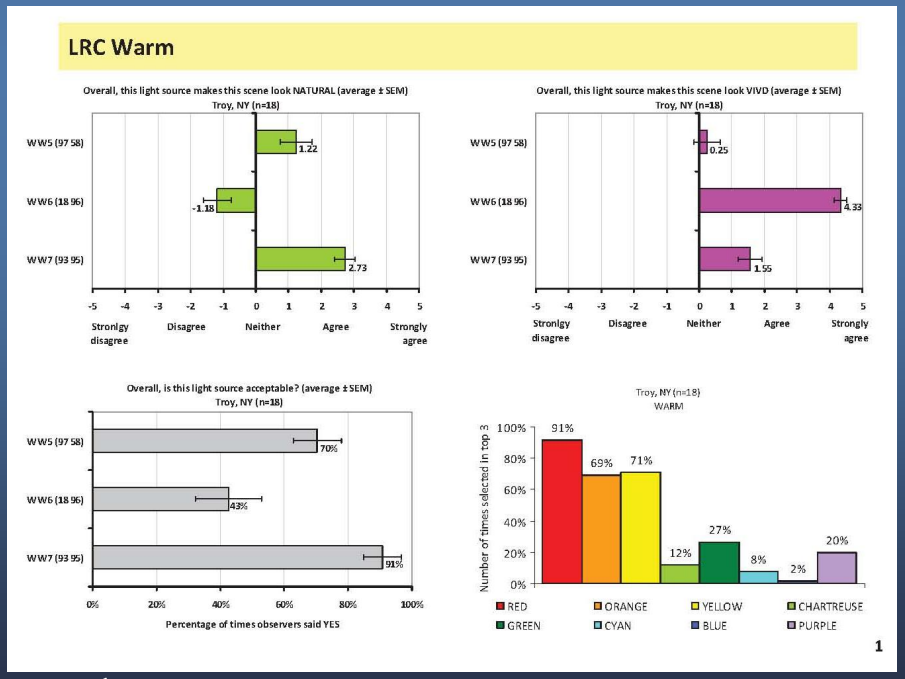


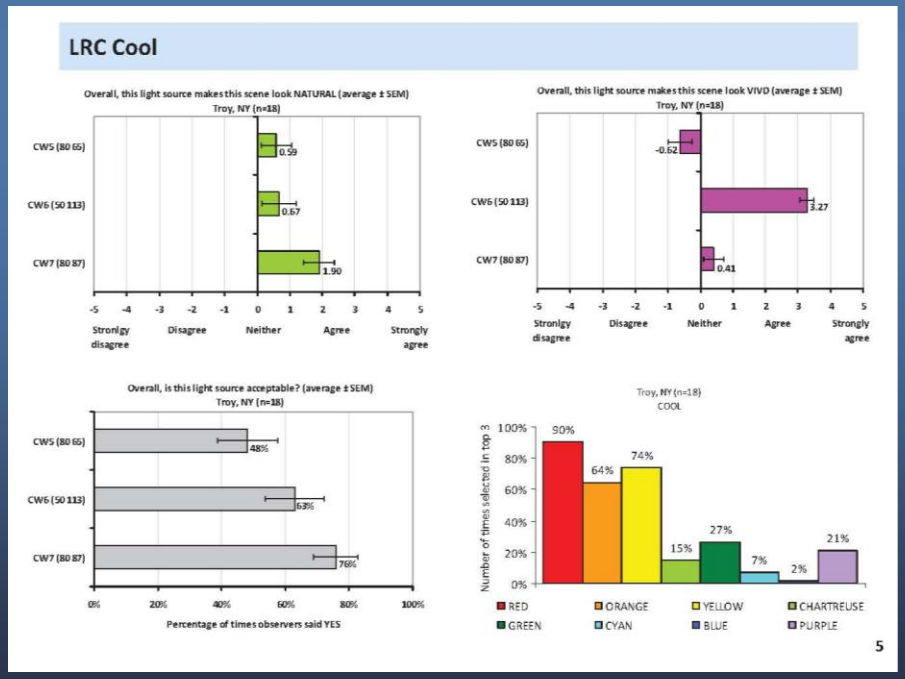


1

Results

- A single metric of color rendering is not capable of describing all dimensions of color rendering – at least two metrics are needed
  - Color rendering index (CRI) >80 and
  - Gamut area index (GAI) between 80 and 100.





www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
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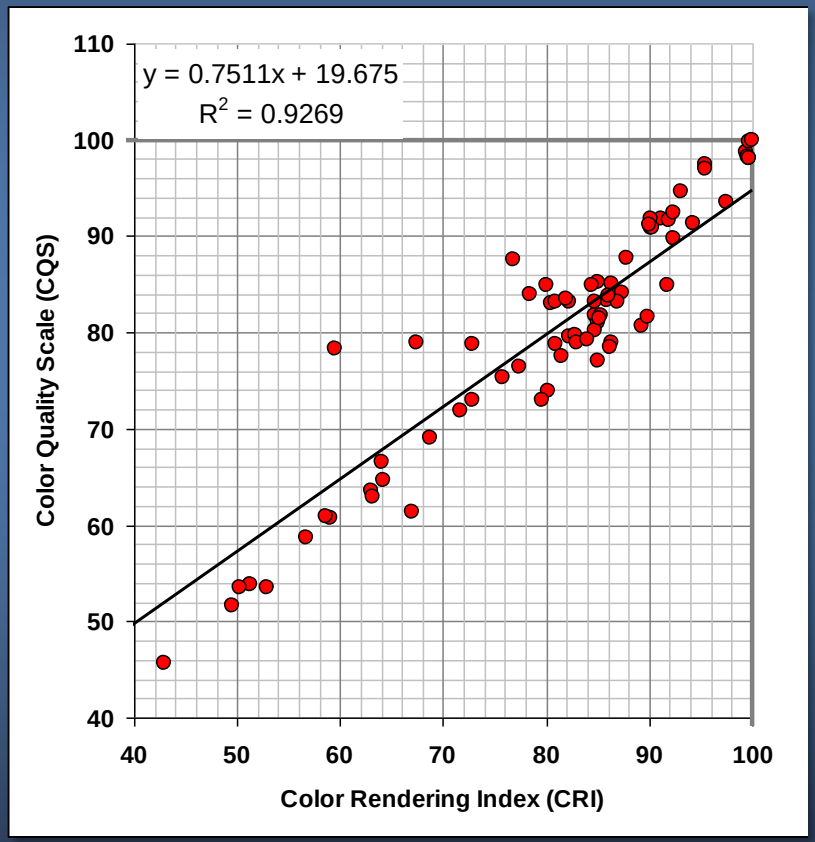
Discussion

- Two metrics needed for "acceptability" and "naturalness"
  - CRI and GAI work
- CQS and R9 could replace CRI
  - But why bother?
- CRI is well established
  - Keep it
- GAI is a simple add-on, and measures a different aspect of color rendering
  - So, why not add predictive power and keep it simple?



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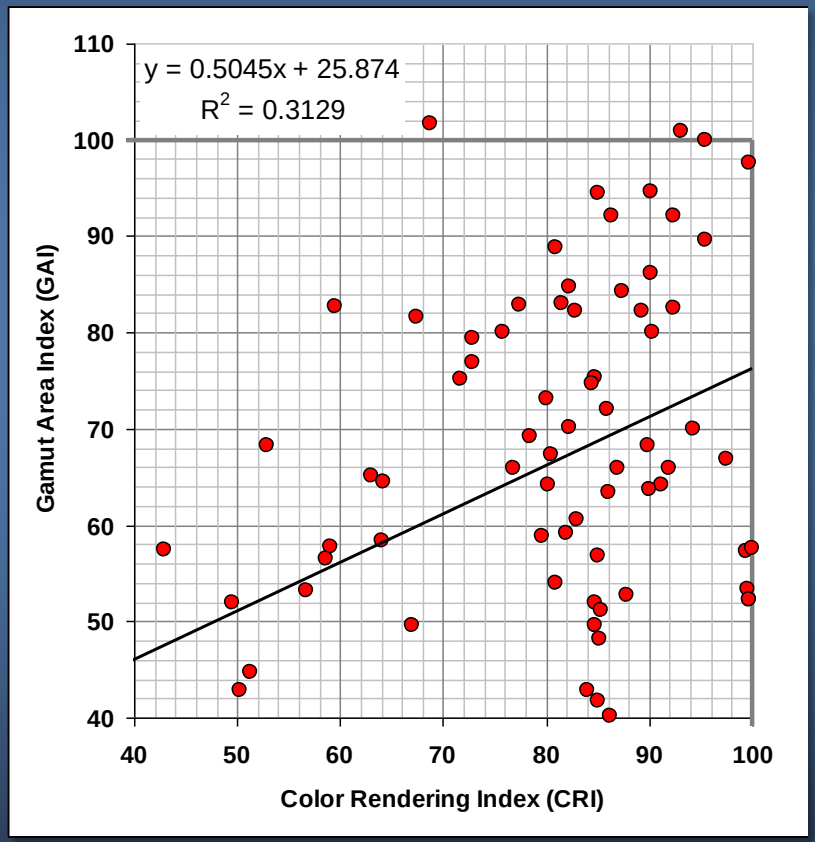

Commercial Light Sources with 80≤ CRI and 80≤ GAI ≤100

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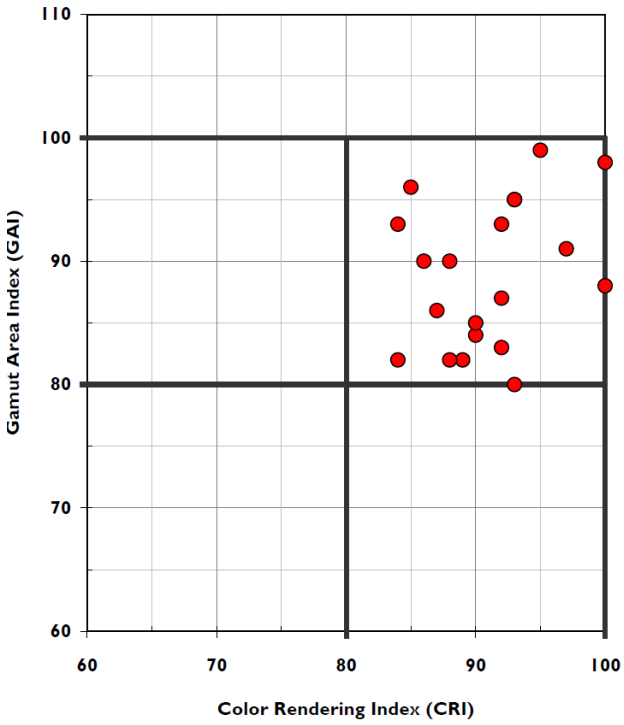
Table 2. Examples of light sources that meet the criteria for CRI (≥80) and GAI (≥80 and ≤100). (The inclusion or mention of any specific brand or product in this table is for illustrative purposes only and does not constitute an endorsement by ASSIST or the Lighting Research Center.)

	Light source	Manufacturer	Product Model	CCT (K)	CRI	GAI
1	Xenon	OSRAM SYLVANIA	1000W	5853	97	91
2	PC-LED	Cree	XRE lamp	4154	84	82
3	PC-LED	Sharp	Zenigata	5097	95	99
4	RGB-LED	Various	Peak wavelengths of 465 nm, 545 nm, and 614 nm	4000	89	82
5	T8	General Electric	F32T8SPX50	4751	87	86
6	T8	Lumiram	Lumichrome 1XX	5960	93	95
7	T8	Verilux	F32T8VLX	6369	85	96
8	T12	OSRAM SYLVANIA	Design50, 40W	4861	90	84
9	T12	General Electric	Sunshine F40C50	4944	92	87
10	T12	Duro-Test	Vita-Lite 5500	5159	88	90
11	T12	Lumiram	Lumichrome 1XC	5207	92	93
12	T12	Philips	Colortone 75	6217	90	85
13	T12	Duro-Test	DAYLITE 65, 40W	6588	93	95
14	MH	Philips	CDM100W/4K	4075	93	80
15	MH	Philips	CDM150W/4K	4197	92	83
16	Daylight		CIE D50	5000	100	88
17	Daylight		CIE D65	6500	100	98



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Color Appearance of Illumination

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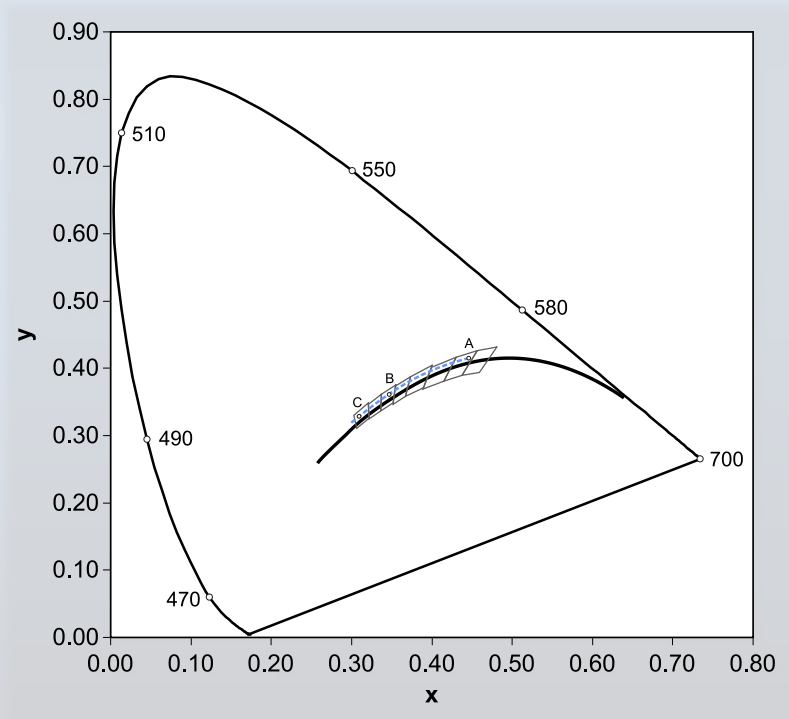
Light source color specification

- Correlated color temperature is the most used metric to specify light source color appearance
  - Based on light source chromaticity



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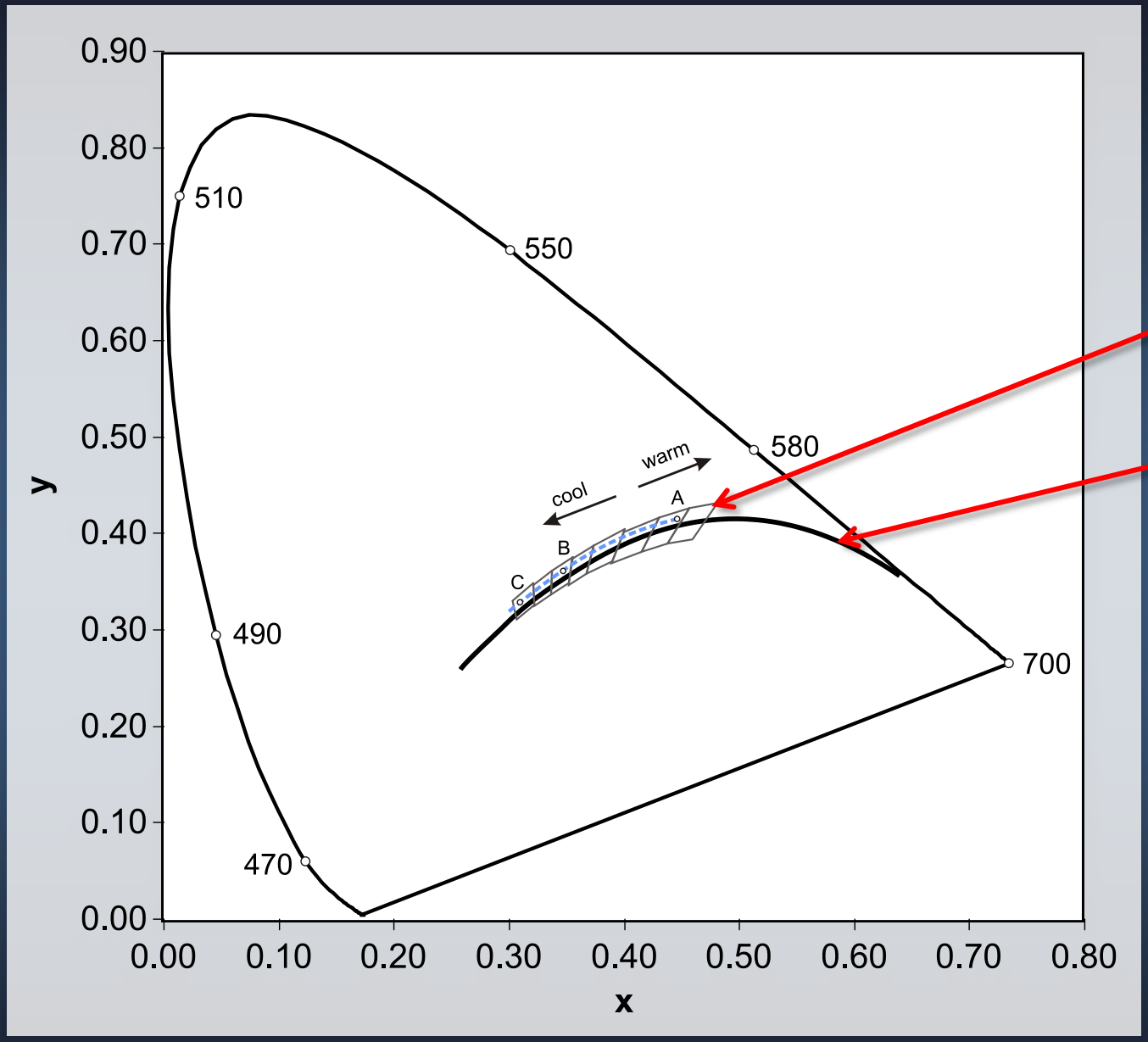
Lamp Type	3.1	1.0	235
Color Consistency	3.1	1.0	228
Spectral Power Distribution (SPD)	2.4	1.2	226
Full-Spectrum Index (FSI)	2.0	1.3	204
Brand Name	1.9	1.2	226
Gamut Area	1.5	1.2	189

(Rating Key: 0 = Not useful; 4 = Very useful)

www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp



ANSI SSL tolerance zones

Blackbody locus

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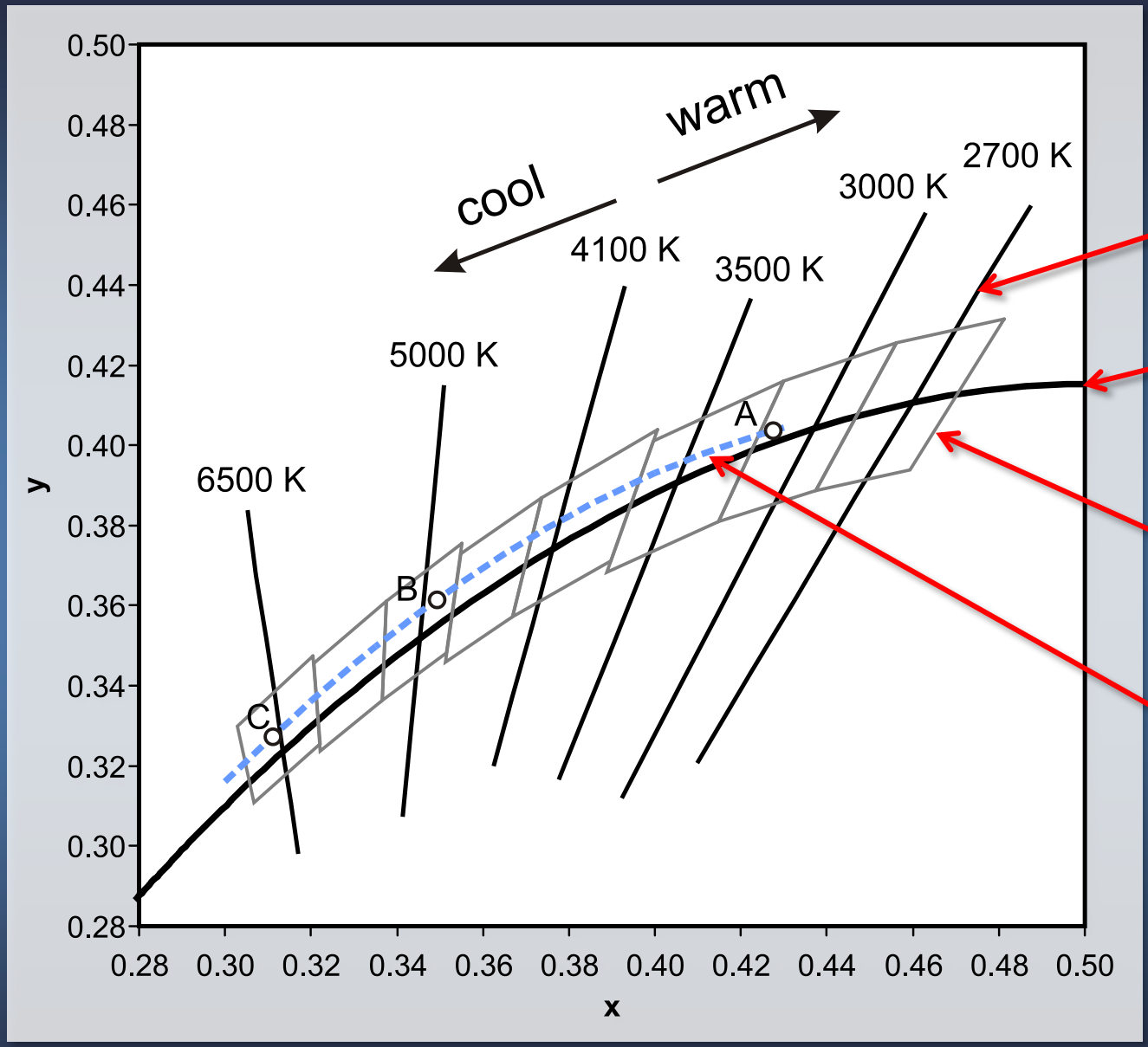
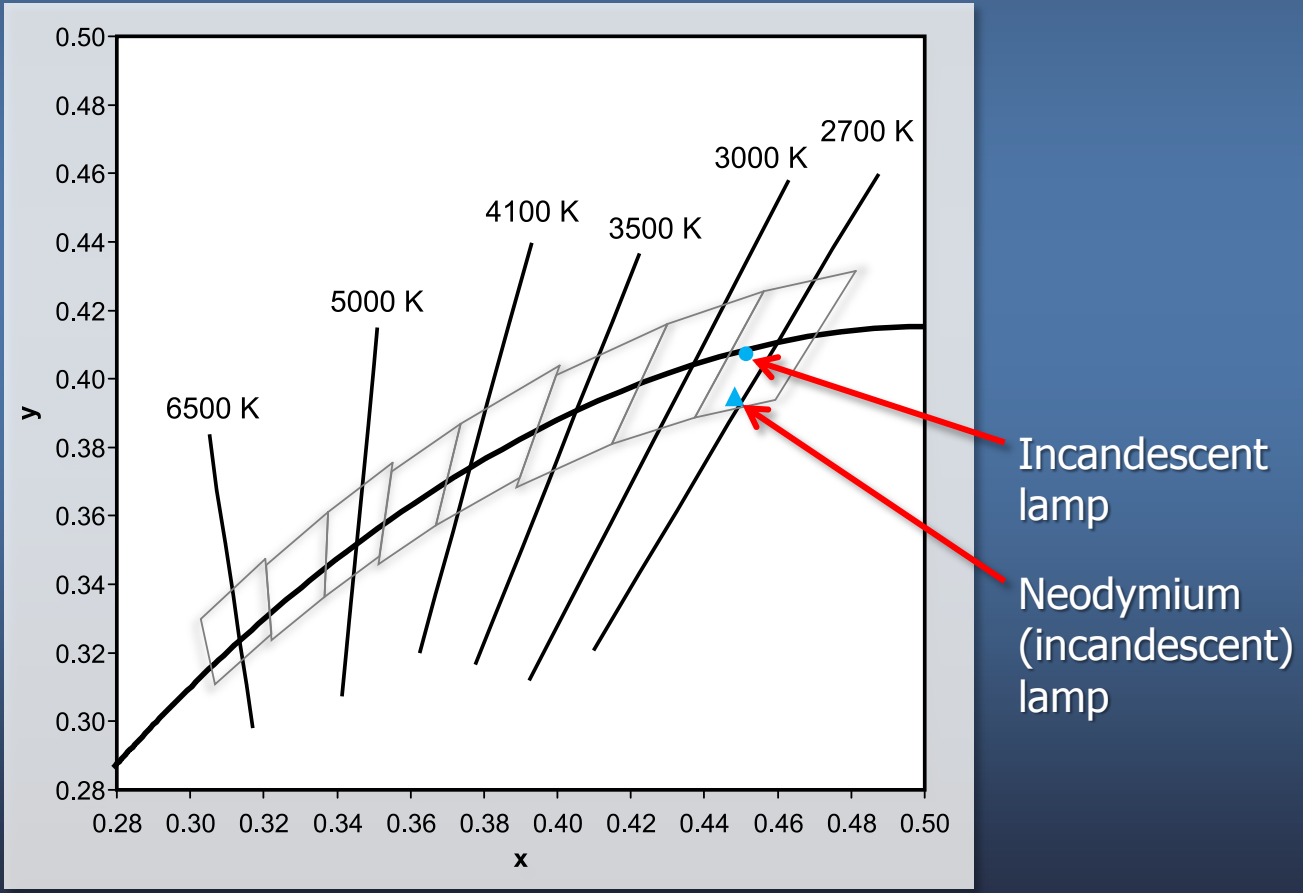
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp



Background

- Many commercial light sources have chromaticities close to the blackbody locus but they may not be considered white



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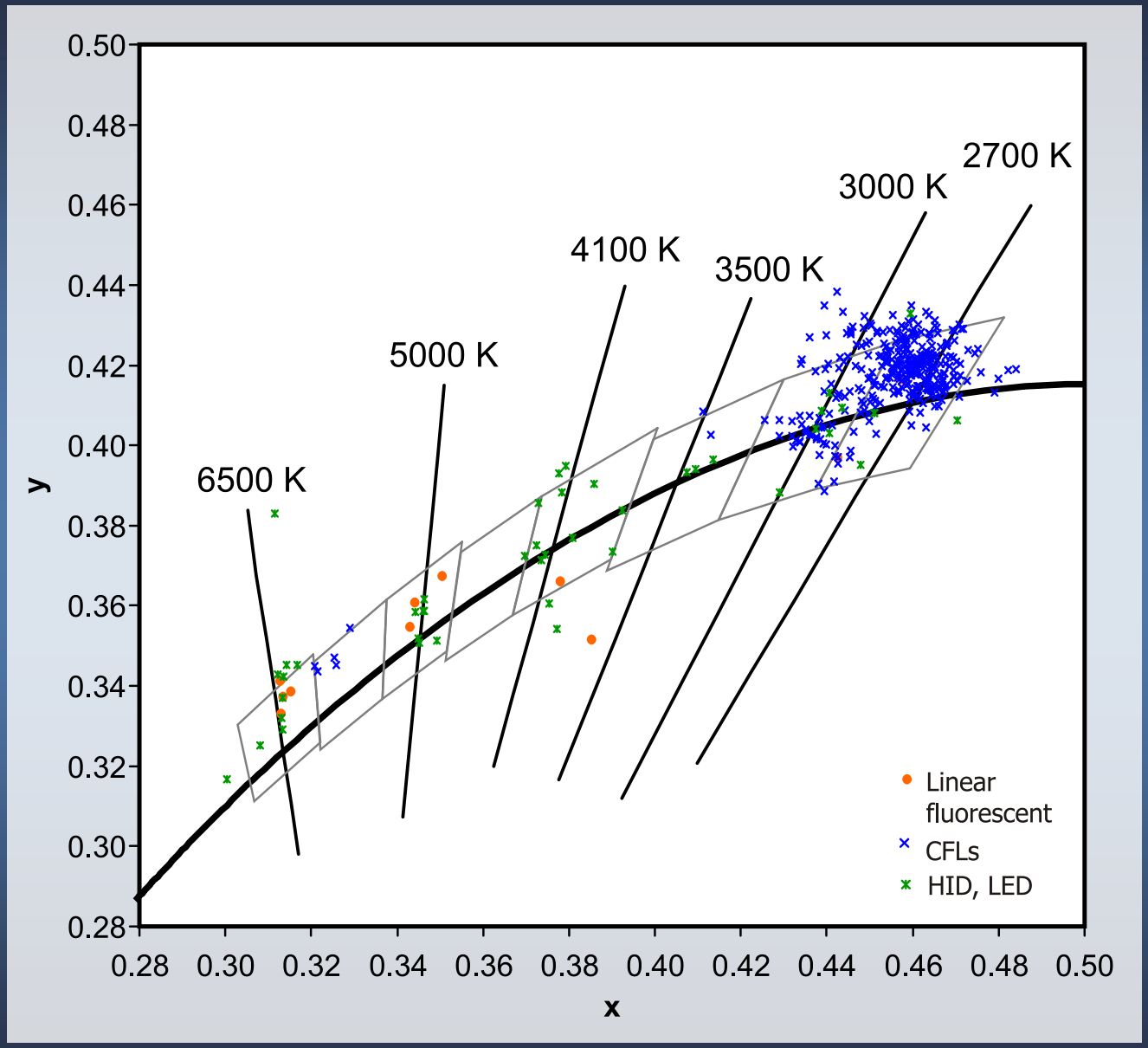

www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

Experimental approach

- Goal: To conduct a laboratory psychophysical experiment to investigate the subjective target chromaticity of white illumination of different CCTs
- Illuminant mode: Viewing box with multiple light sources
  - Computer controlled to produce specific chromaticities and light levels
  - Active feedback provided stability
  - Horizontal illuminance: 30 fc
- Six correlated color temperatures 2700-6500 K
- Seven chromaticities along each CCT line
- One viewing distance, 12” from the opening of the box

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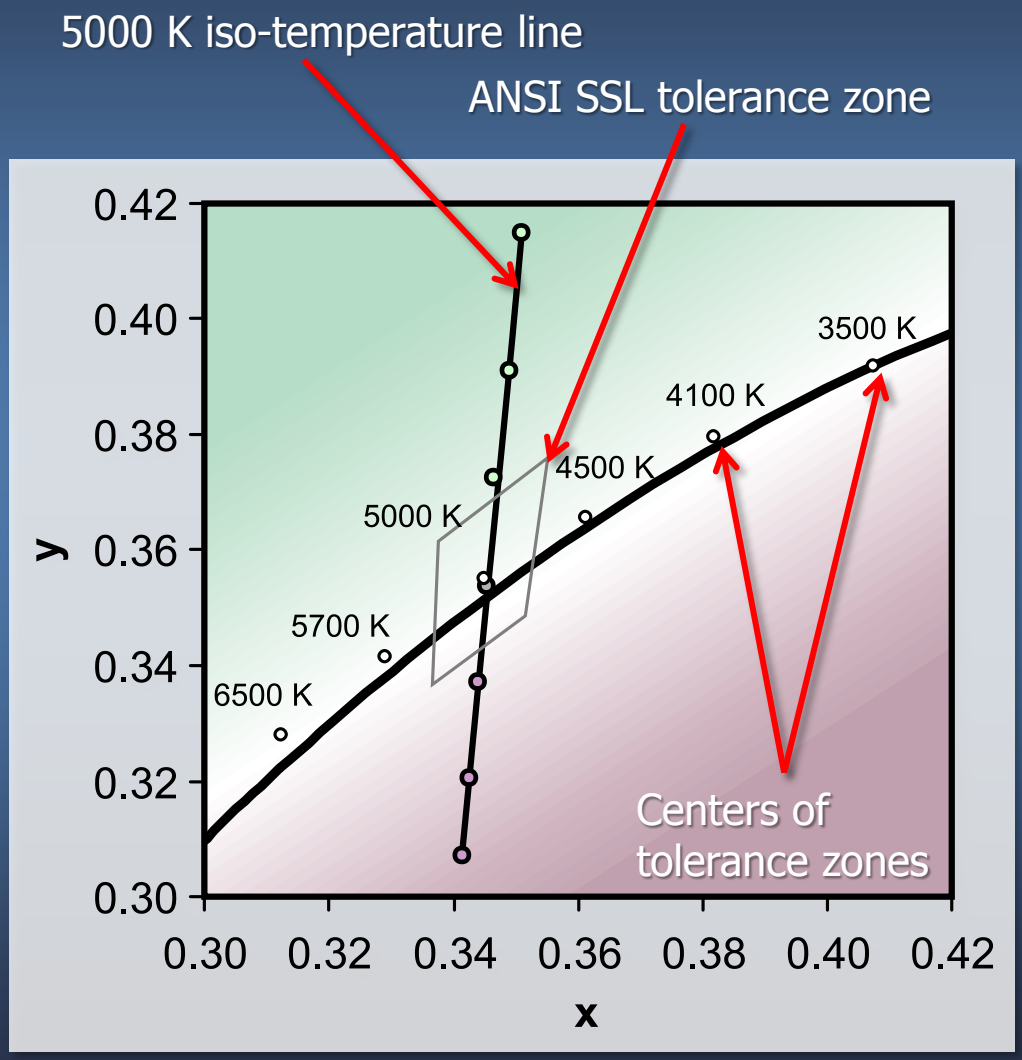
Experimental approach

- Subjective responses
  - Immediately after seeing the light source
    - Hue of light source: green/yellow or purple/violet
    - Percent of hue relative to a pure white
  - After 45 sec adaptation
    - Hue of light source: green/yellow or purple/violet
    - Percent of hue relative to a pure white



Results

- With the data for each CCT, the white point was estimated for each question (hue choice, hue estimate) and for each adaptation (immediate, 45 seconds)

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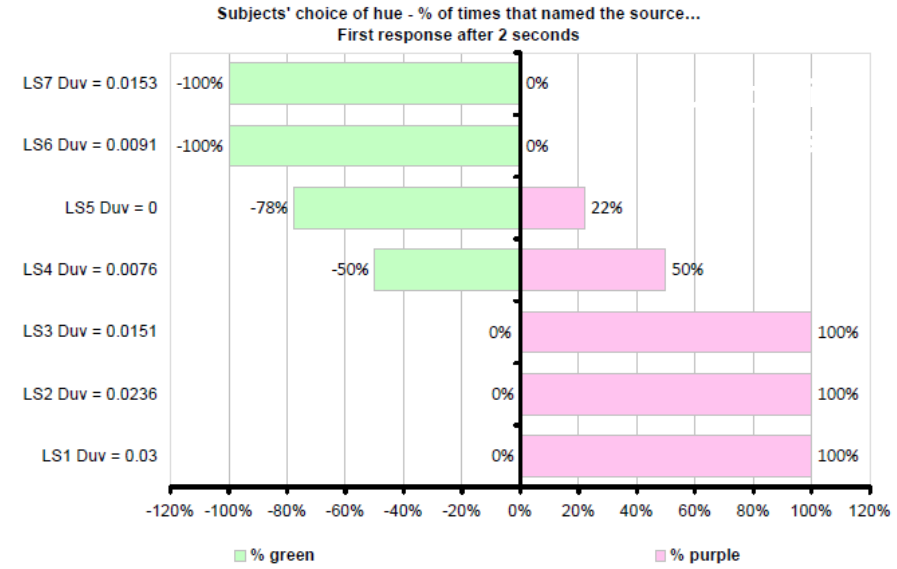
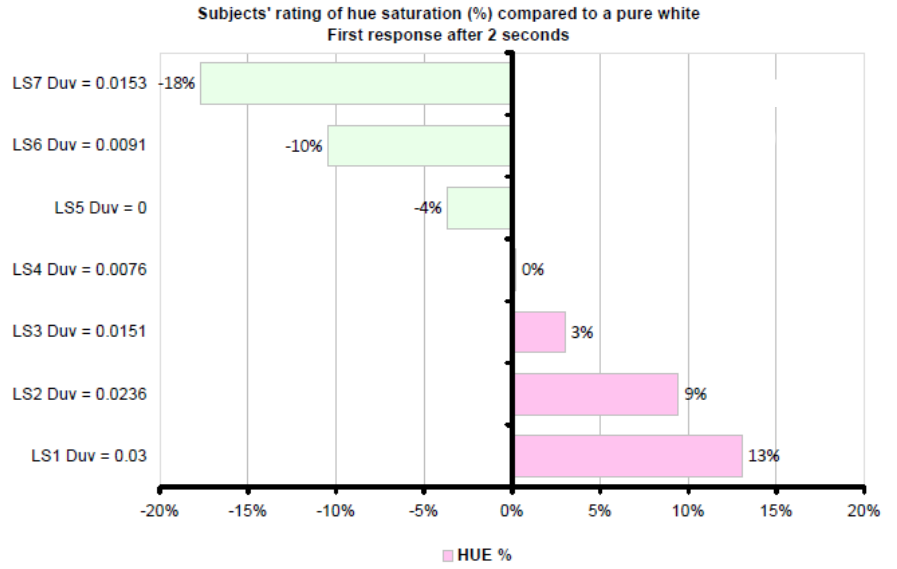
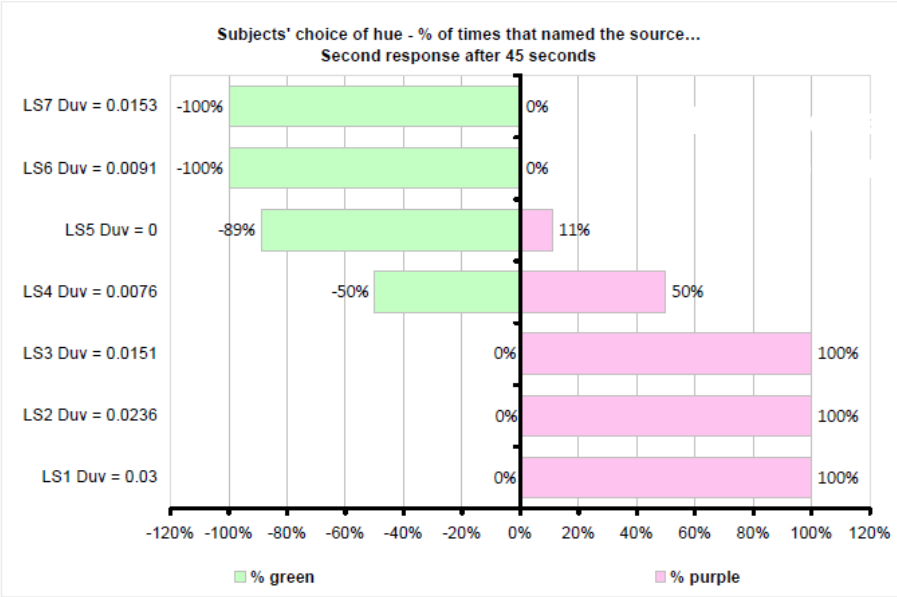
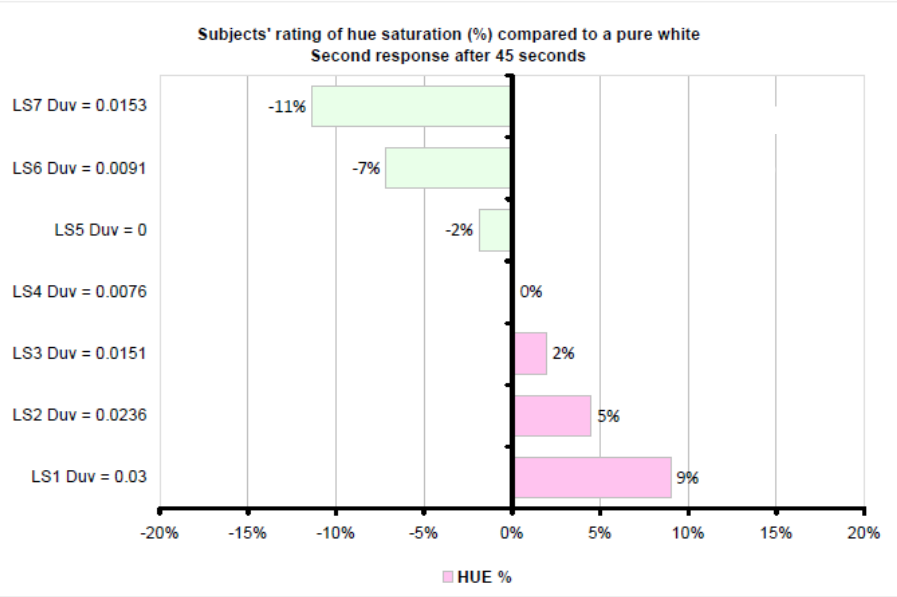
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

Results: example



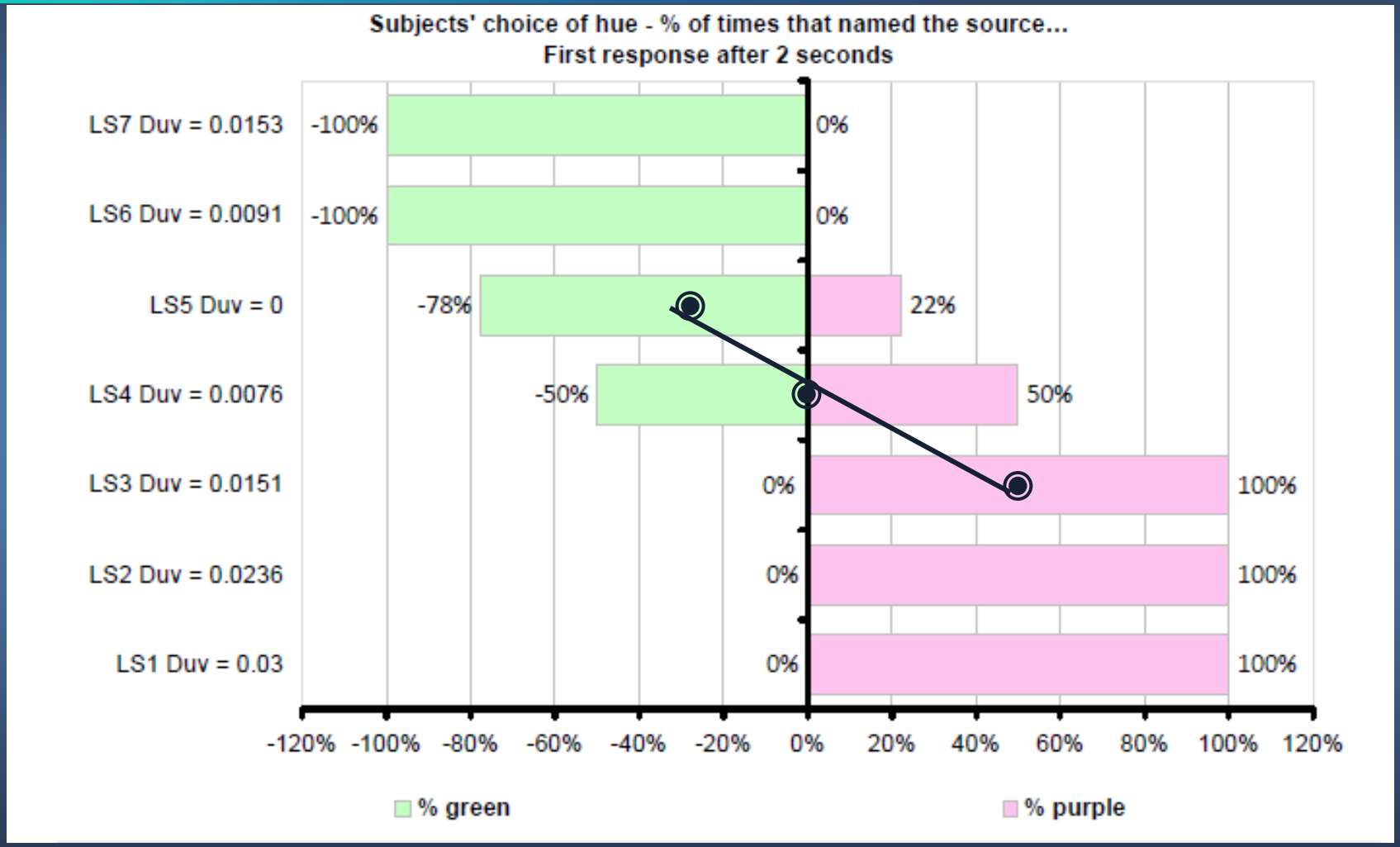






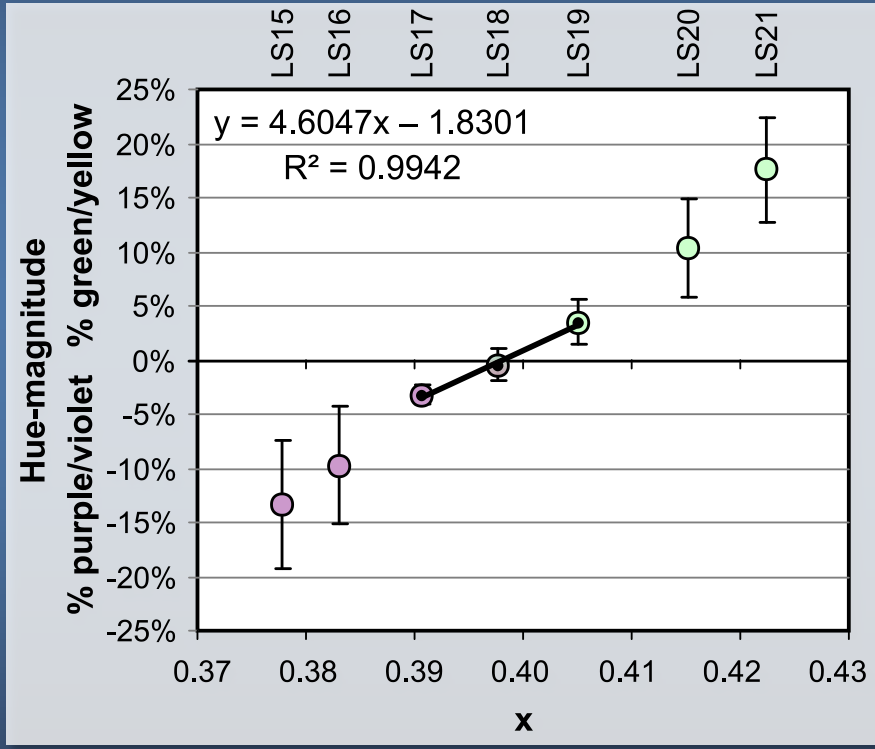
www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

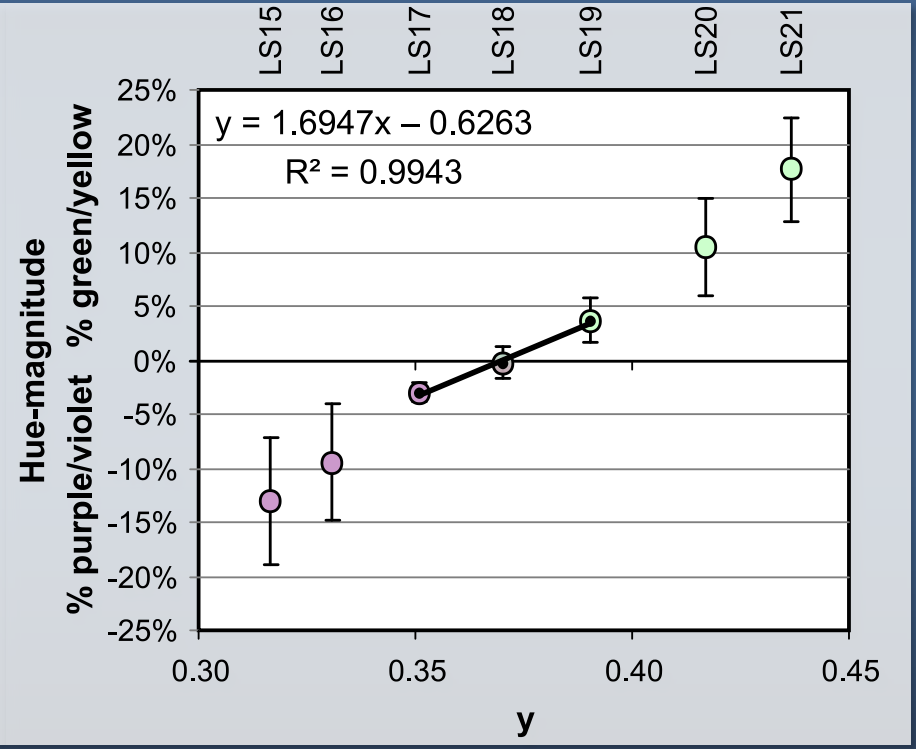
Results: Hue choice



Hue magnitude

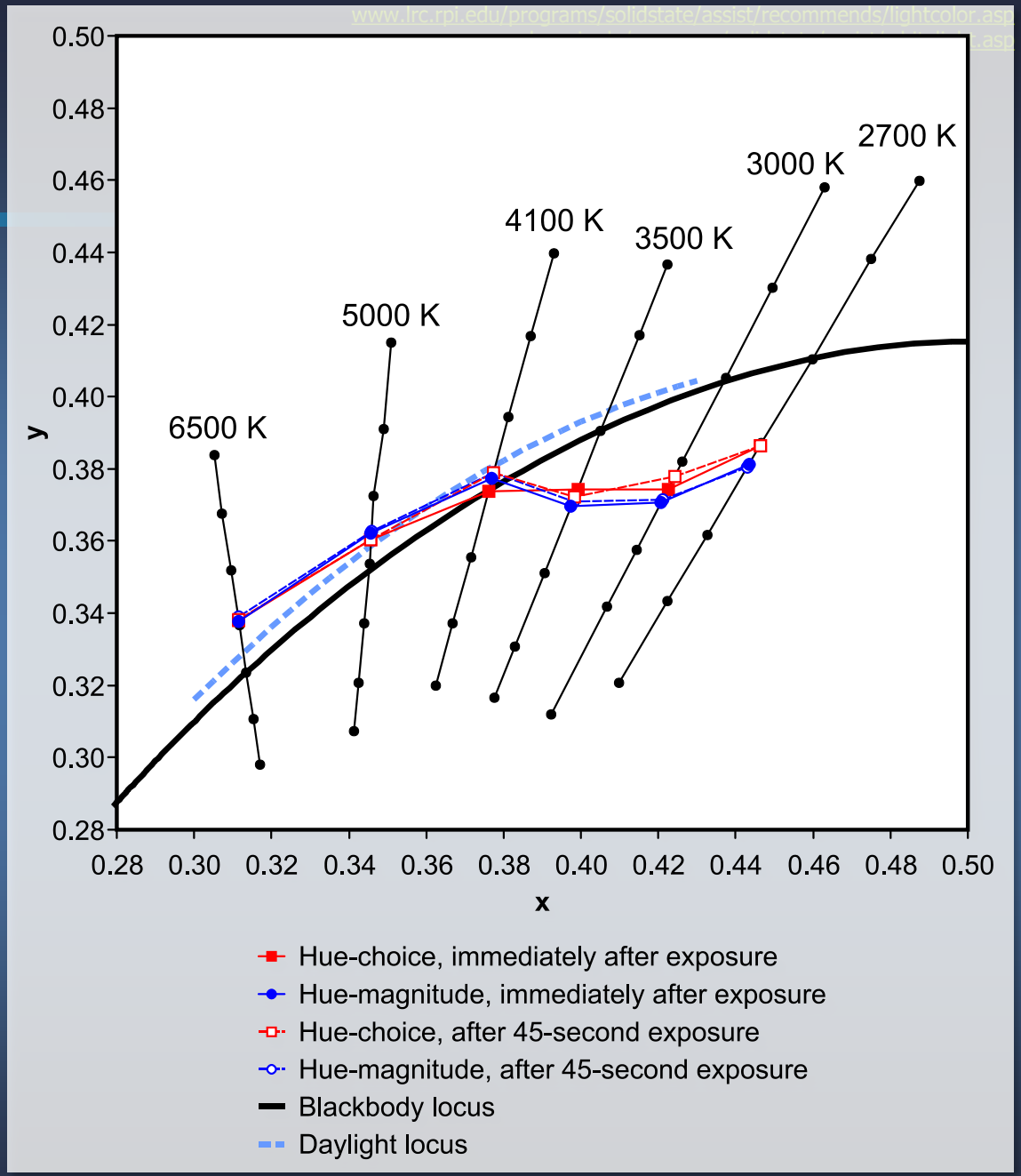
Immediate Response





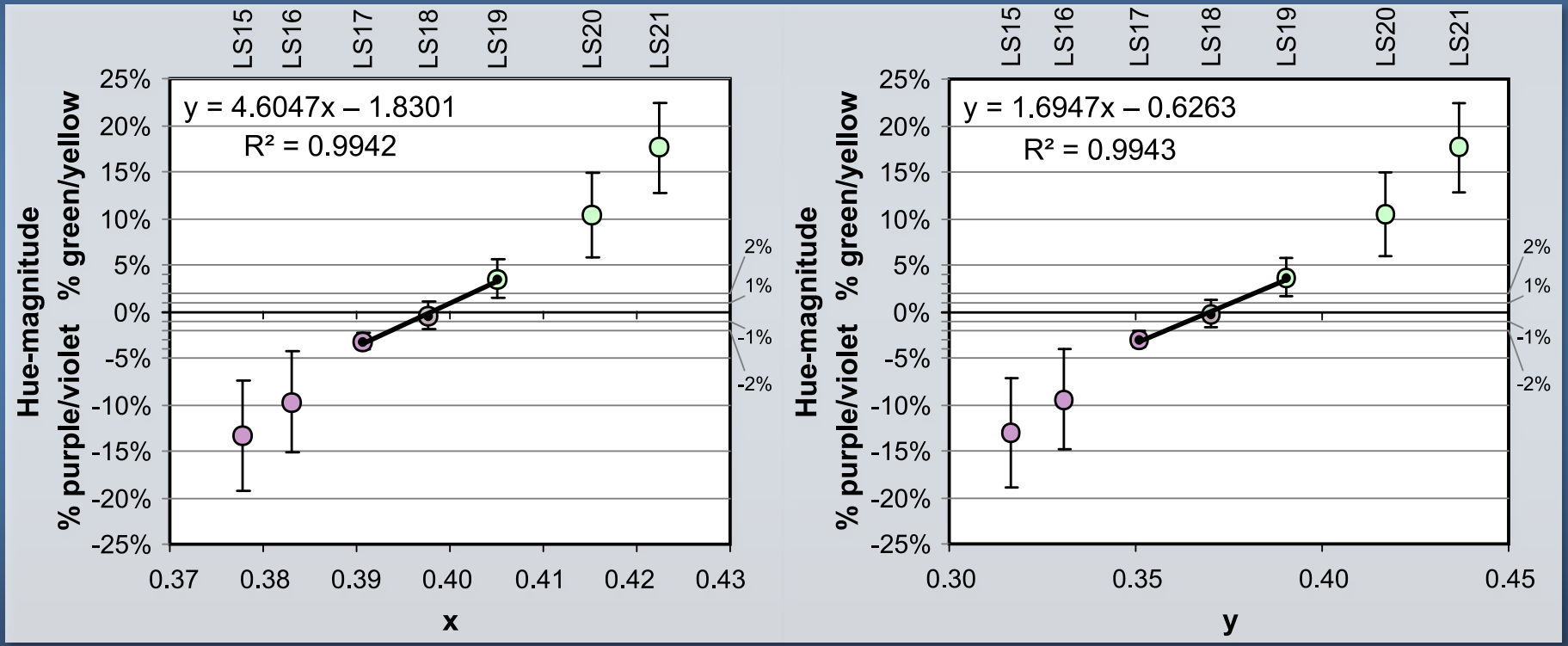
Results

- The four "white points" are close together for each CCT
  - White is white; does not change with time
- White points for CCTs 3500 K and lower are below the blackbody locus
  - And above the blackbody locus for 4100 K and above



Hue magnitude (tint)

Immediate Response



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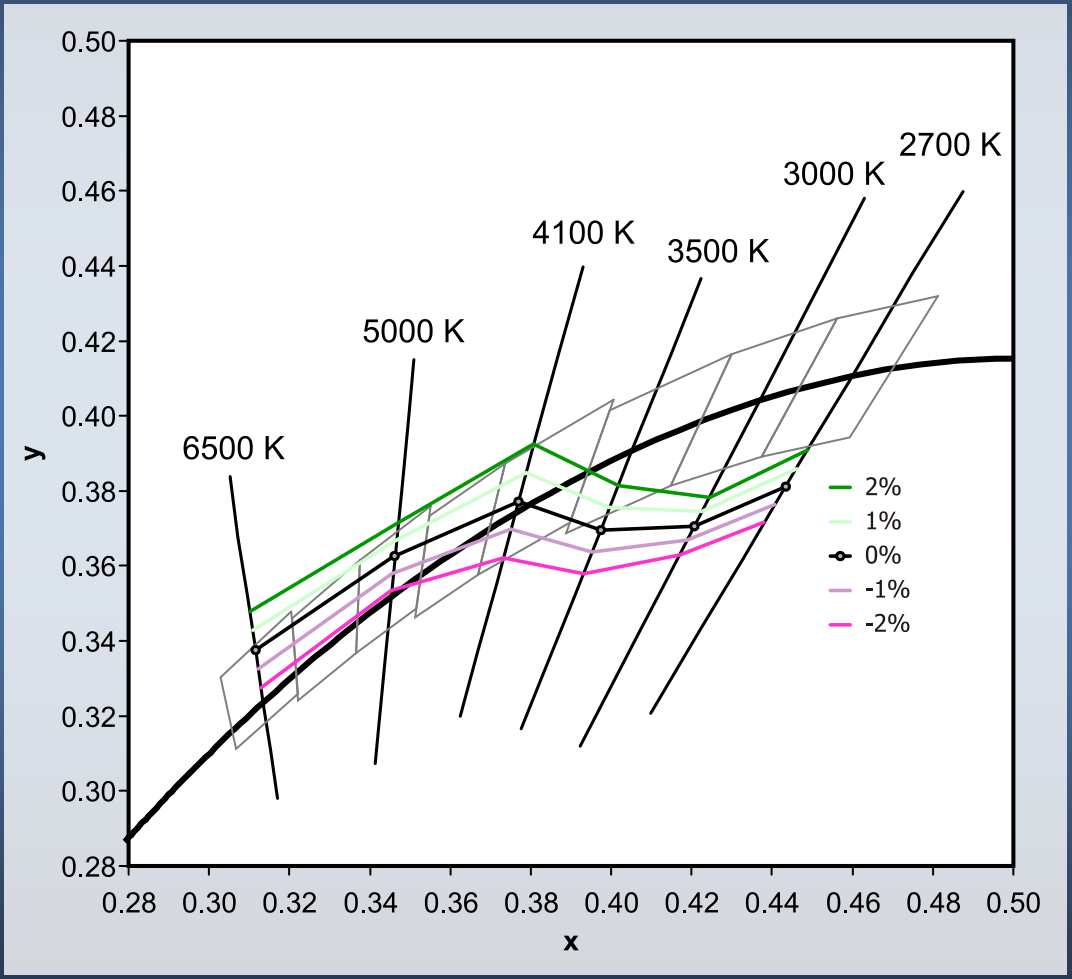
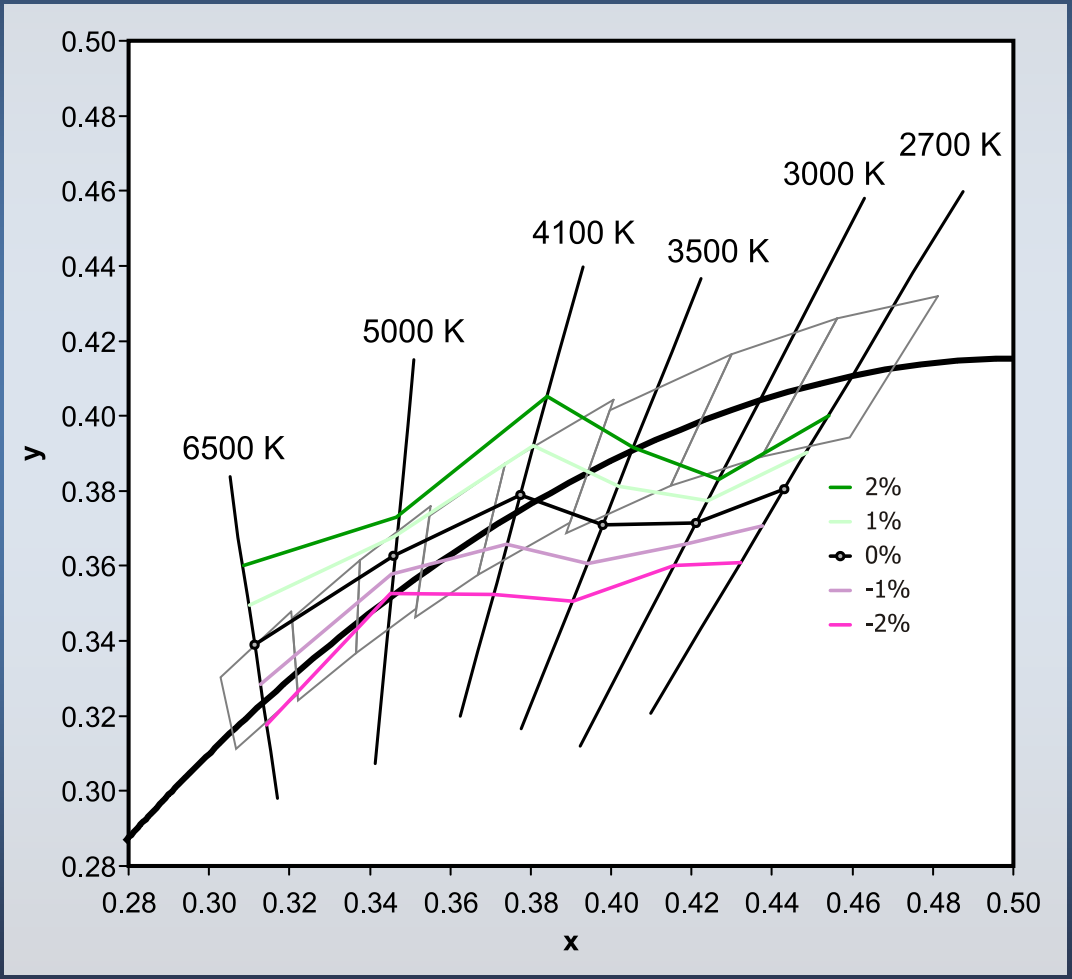
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp

Iso-contours for judgments immediately following presentations



Iso-contours for judgments 45 s after presentations

www.lrc.rpi.edu/programs/solidstate/assist/recommends/lightcolor.asp
www.lrc.rpi.edu/programs/solidstate/assist/whitelight.asp



White points remain in the same place but range -2% to +2% increases because of the chromatic adaptation that occurs over time

- Sources appear less saturated, i.e., with less tint

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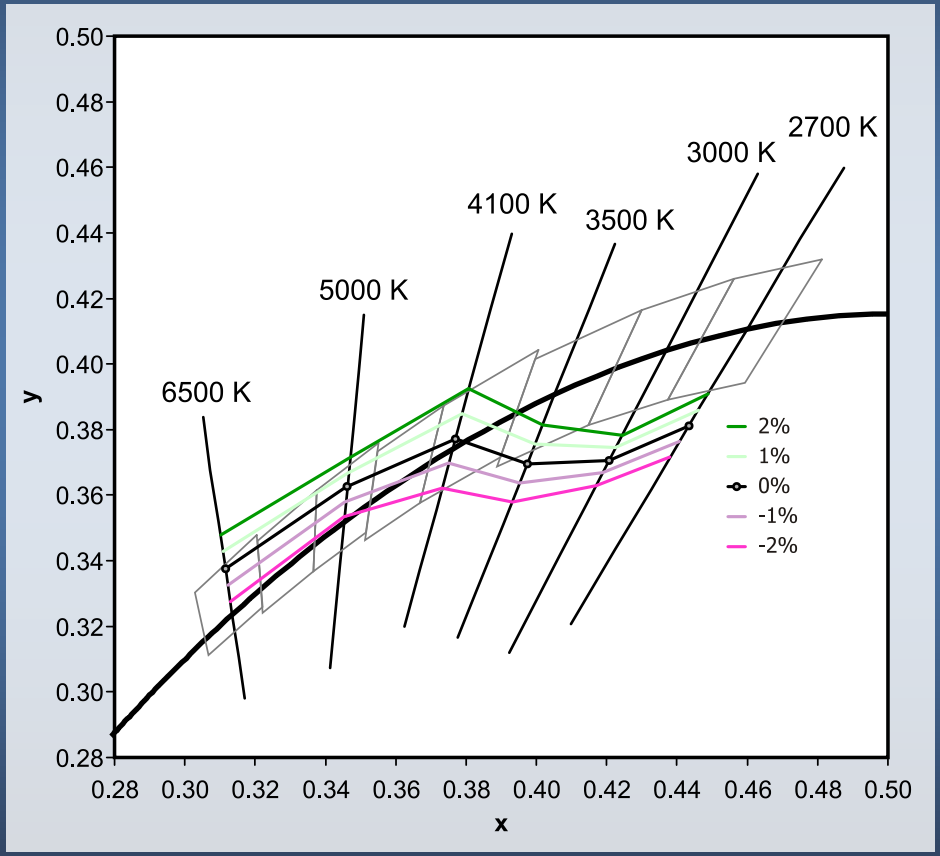
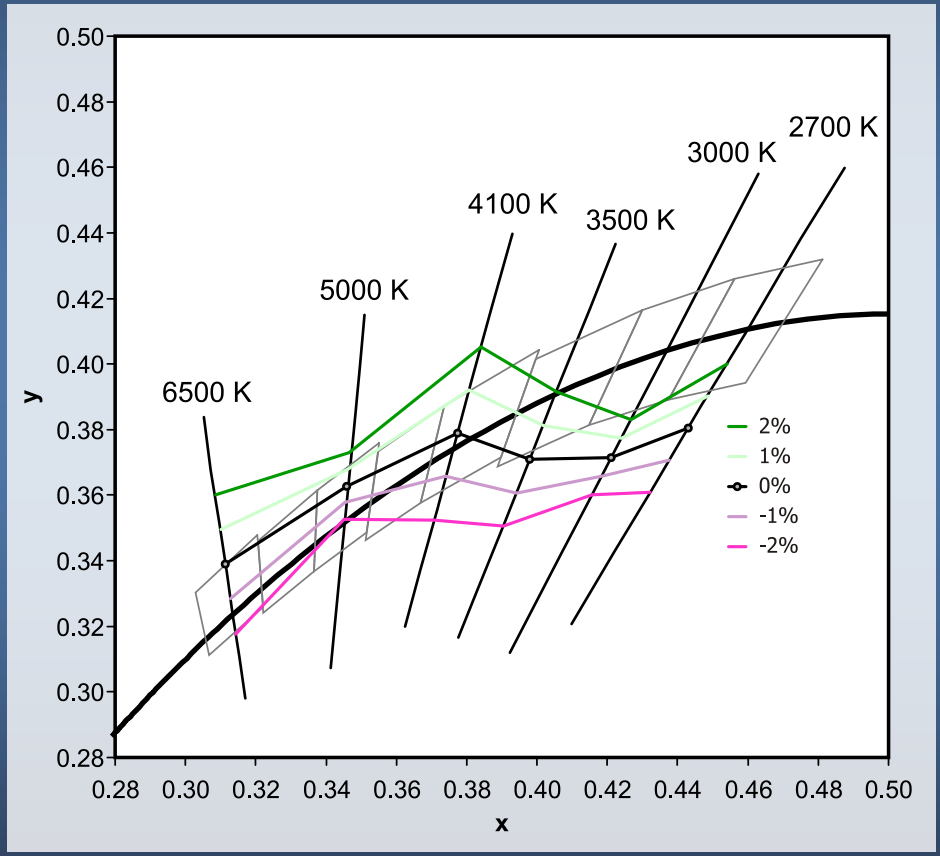
Discussion

Judgment: Immediate



Judgment: After 45 sec



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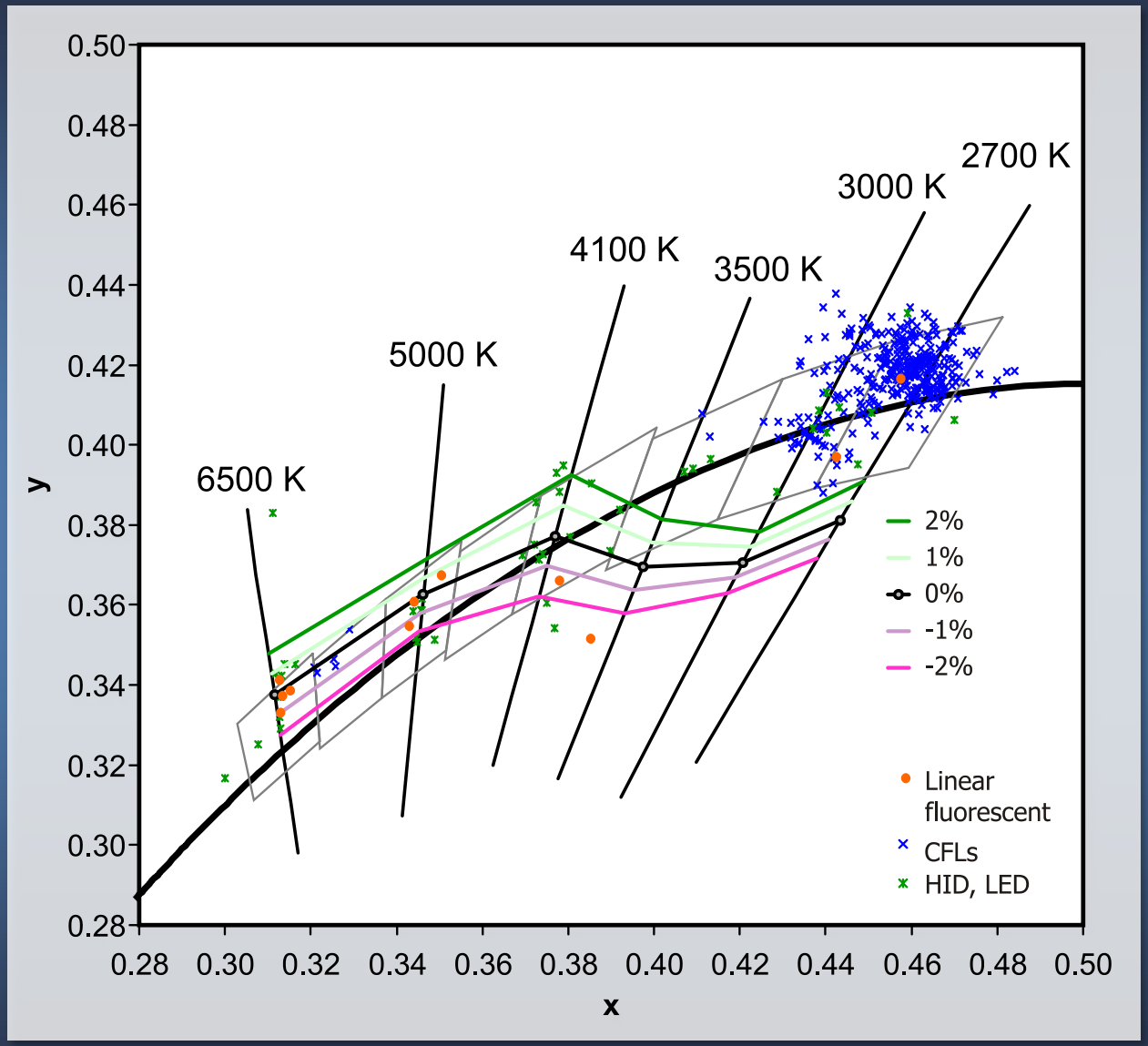

Lighting Research Center

Rensselaer

Recommendations for general illumination: Class A color light sources

a) Have a chromaticity on or near the "white" body line
b) CRI > 80 and 80 ≤ GAI ≤ 100
c) Are consistent in chromaticity

Freyssinier, J.P. and M.S. Rea. 2012. Class A color classification for light sources used in general illumination. *Light Sources 2012: Proceedings of the 13th International Symposium on the Science and Technology of Lighting*, June 24-29, 2012, Troy, New York, pp. 337–338. Sheffield, UK: Foundation for the Advancement of the Science and Technology of Light Sources.

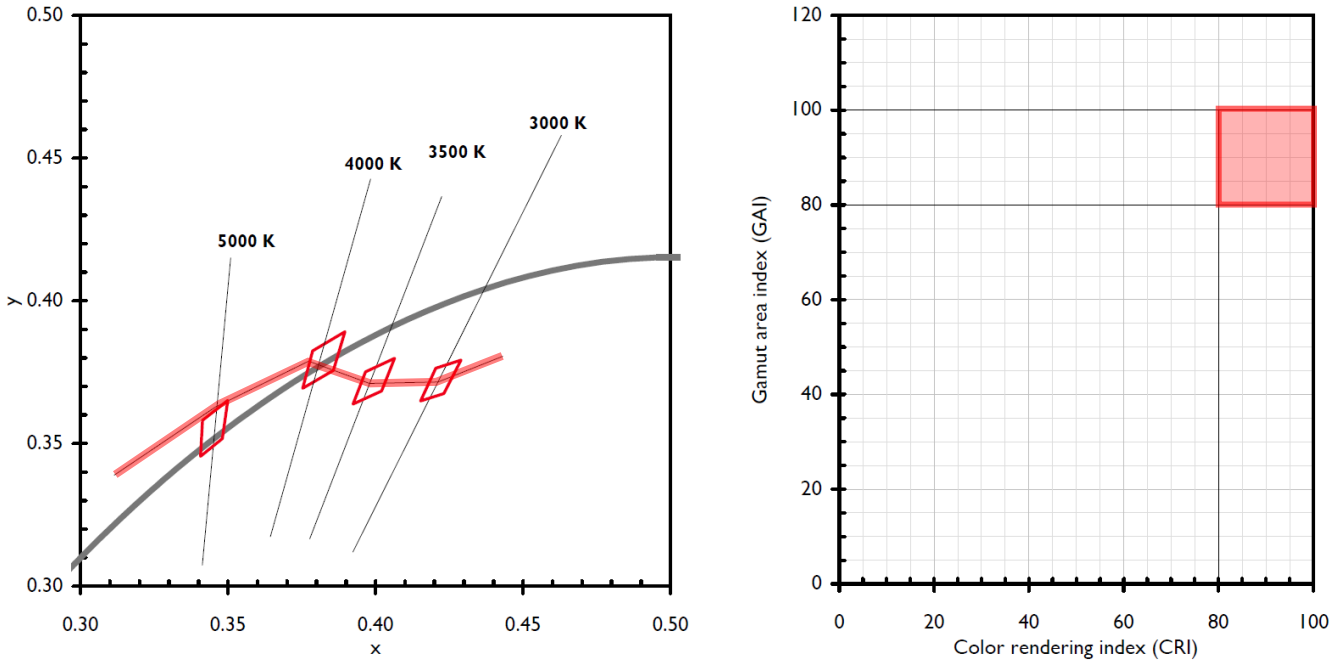

Figure 3. Class A target zones for "white" illumination (left panel) and good color rendering properties (CRI≥80 and 80≤GAI≤100; right panel).

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Implications

- Same CCT can have different hues/tints
- Changes in CCT along the blackbody are not a dimension of whiteness
- These data might be used to map commercial (or in development) light sources
- Knowing the location of the "white points" might be a foundation to plan and interpret experiments of preferred target chromaticities
  - Important to avoid confounding with the color rendering properties of the source
- Context-based: retail, residential, outdoor

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Implications

- Examples of when Class A is not necessarily what is needed
  - Meat lamps
  - Candlelight dinner
  - HPS parking lot
  - Plant growth

- Reminder: Light level is important for good color rendering; higher light levels give better color rendering

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Thank you!

Acknowledgements

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- Alliance for Solid-State Illumination Systems and Technologies (ASSIST):

  3M, Acuity, Amerlux, Bridgelux, Cirrus Logic, Cooper Lighting, Cree, Dow Corning, Federal Aviation Administration, General Electric, Industrial Technology Research Institute, Intematix, LG Electronics, LG Innotek, Lighting Science, LiteOn, New York State Energy Research and Development Authority, OSRAM Sylvania/OSRAM Opto Semiconductors, Philips Lighting, Posco LED, Seoul Lighting, Sharp, Toshiba, United States Environmental Protection Agency, WattStopper

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