Psychophysical Evaluations of Various Color Rendering from LED-based Architectural Lighting

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OUTLINE:

- Introduction
- Motivation
- Hypothesis and Proposal
- Experiments – Phase 1
- Experiments – Phase 2
- Conclusions

ARCHITECTURAL LIGHTING & LEDs

CONTROLLABILITY: Great Opportunity

Colored Lighting Effects

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Manipulation of WHITE LIGHT Spectrum:

Luminance (Brightness) & Color Temperature: color appearance of light

Color Rendering: color appearance of objects under such light

Empower the Design, Improve Visual Quality & Further increase Energy Efficiency.

Color Rendering - Color Appearance of Illuminated Objects

Variations of Color Rendering

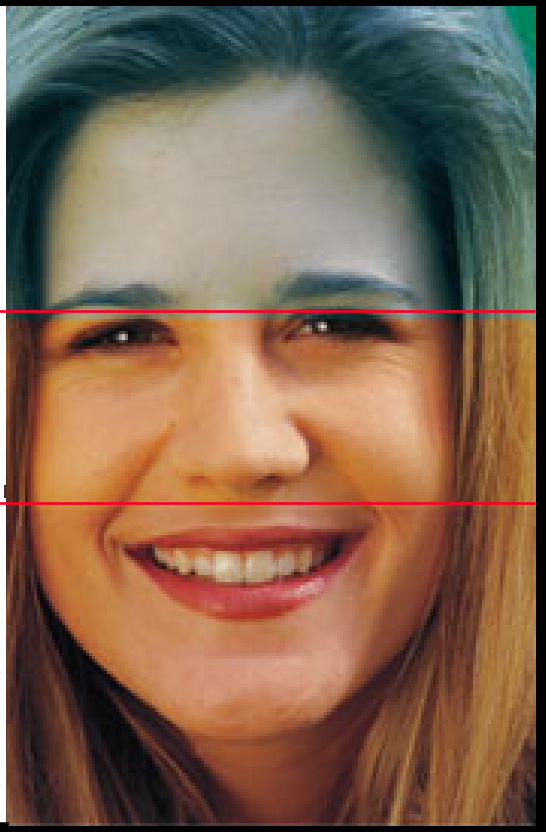
Color Rendering - Food

Color Rendering - Human Skin

Low Color Rendering

Medium Color Rendering

High Color Rendering

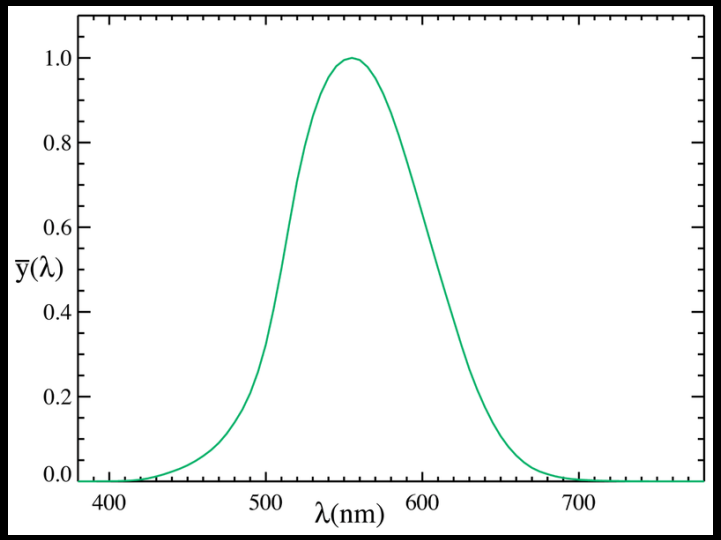


Color Rendering Modulation: WHY WOULD WE DO THAT?

Manipulate spectral components of white illuminants to:

- Enhance objects, food, people – Increasing spectral emission that will enhance appearance (boost saturation) of objects in the scene.

- Save energy & reduce waste - Increasing spectral emission in those regions where the eye response is greatest (green/yellow region).



Human eye spectral sensitivity - V(λ) function.

Color Rendering Modulation: WHY WOULD WE DO THAT?

Main Motivation – possibility of a novel Control Strategy:

Reduce Color Rendering in unoccupied areas to further improve energy savings and tackle waste.

Strategy based on two principles:

- Fundamental trade-off between color rendering and luminous efficacy.

  Luminous efficacy is driven by the human eye spectral sensitivity demonstrated by the V(λ) function.

- While changing color rendering, light levels and CCT can stay constant.

  Appearance of the modified light can stay the same. Only illuminated objects will change.

Color Rendering Modulation: A GRAND CONCEPT?

Occupied HIGHT CRI	Partially Occupied HIGHT CRI - only here LOW CRI - surrounds	Unoccupied LOW CRI
		
NO SAVINGS	SOME SAVINGS	MAXIMUM SAVINGS

EXAMPLE: Changing from a CRI of 90 to a CRI of 48 can **reduce energy consumption by 23%.**
This change will be less noticeable and **less objectionable than dimming 23%.**

PSYCHOPHYSICAL EXPERIMENTS

Can we Change Color Rendering Unnoticeably?

Hypothesis: Yes, we can have lighting changing from 'energy saving mode' (low CRI) to 'quality mode' (high CRI) "invisibly".

PHASE 1 – TWO PILOT EXPERIMENTAL SECTIONS USING:

- DOUBLE BOOTH
- COLOR SAMPLES
- DISCRETE MODULATION OF CR
- DIRECT OBSERVATION

PHASE 2 - FINAL EXPERIMENTAL SECTIONS USING:

- FULL-SCALE ARCHITECTURAL MOCK-UP, SIMULATINGN REAL LIFE SCENE
- THREE ANGLES OF OBSERVATION 0°, 10° & 20° from stimuli;
- CONTINUOUS MODULATION OF CR

Phase 1 - Baseline Experiments

DOUBLE BOOTH + COLOR SAMPLES

Phase 1A	Phase 1B
Side-by-Side – Direct observation	Opposite Side – Sequential observation

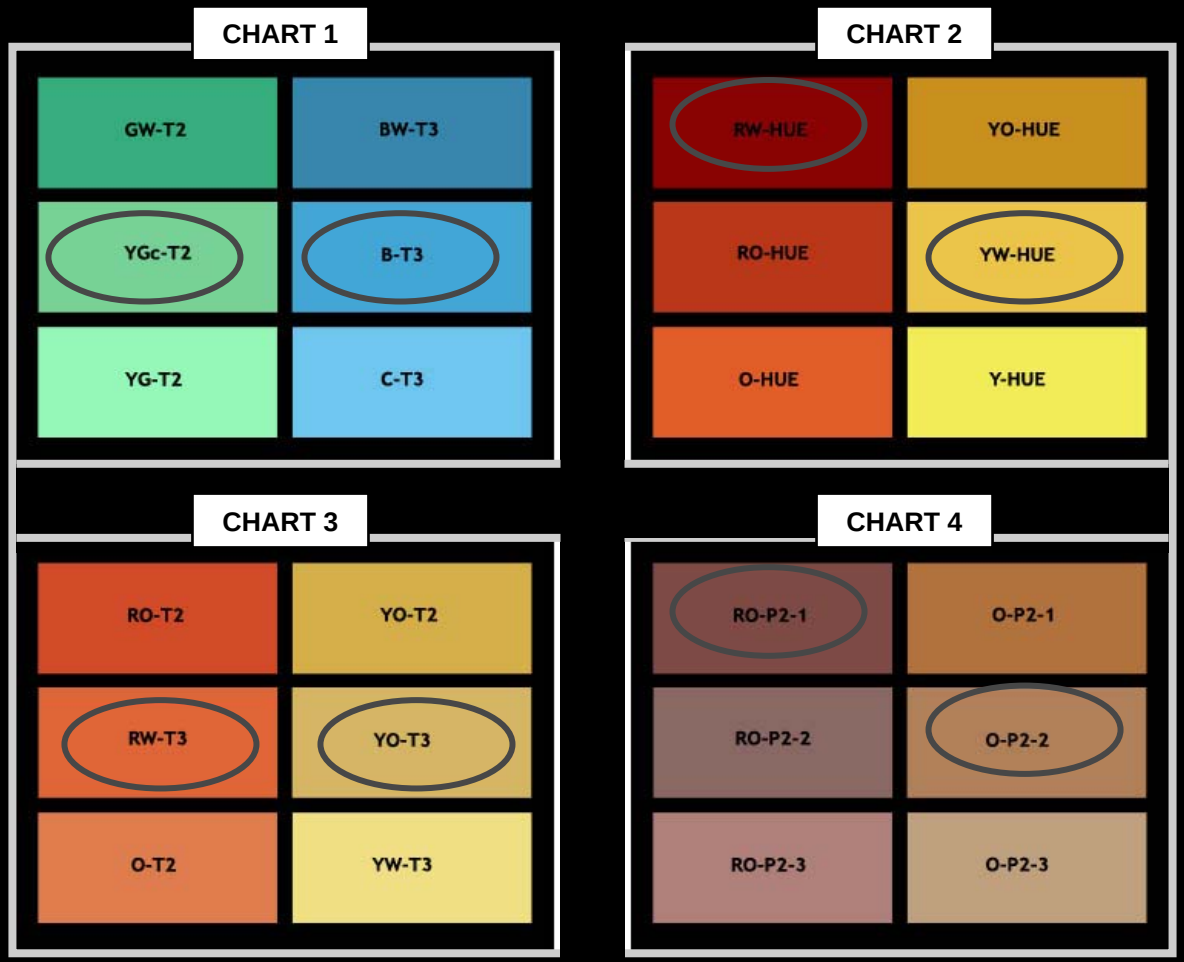
Color temperature & Light Levels - Constant at 3,000 K & 280 lux
Color Rendering – Discrete Sequencing from Ra 37 to 88 (manually switch through spectra)

QUESTION: The color sample in Booth #1 looks, < > compared to the sample in Booth #2?

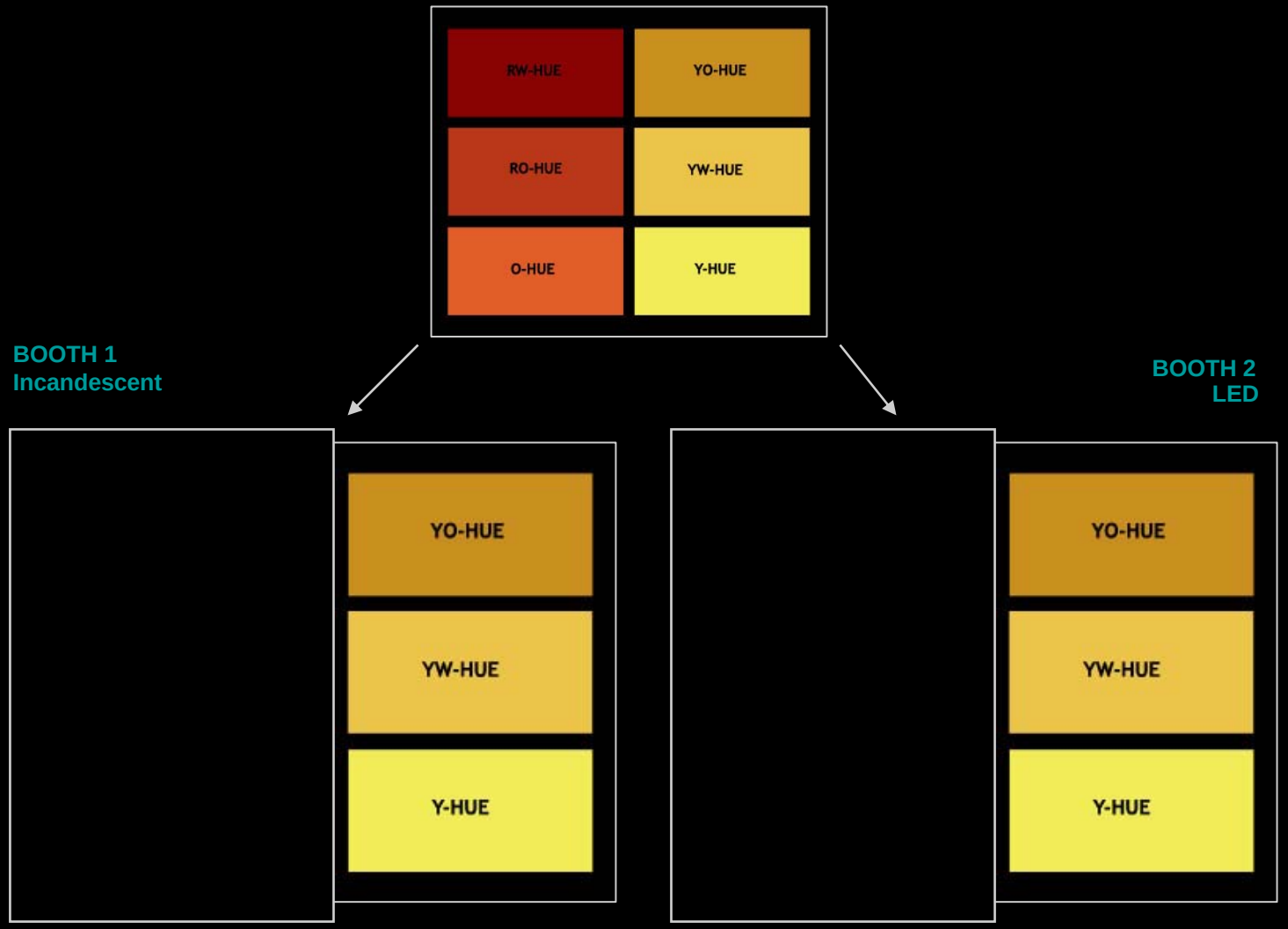
THE SAME	JUST NOTICEABLY DIFFERENCE	DIFFERENT	VERY DIFFERENT

PHASE 1 - Experiment Set-up - Color Samples

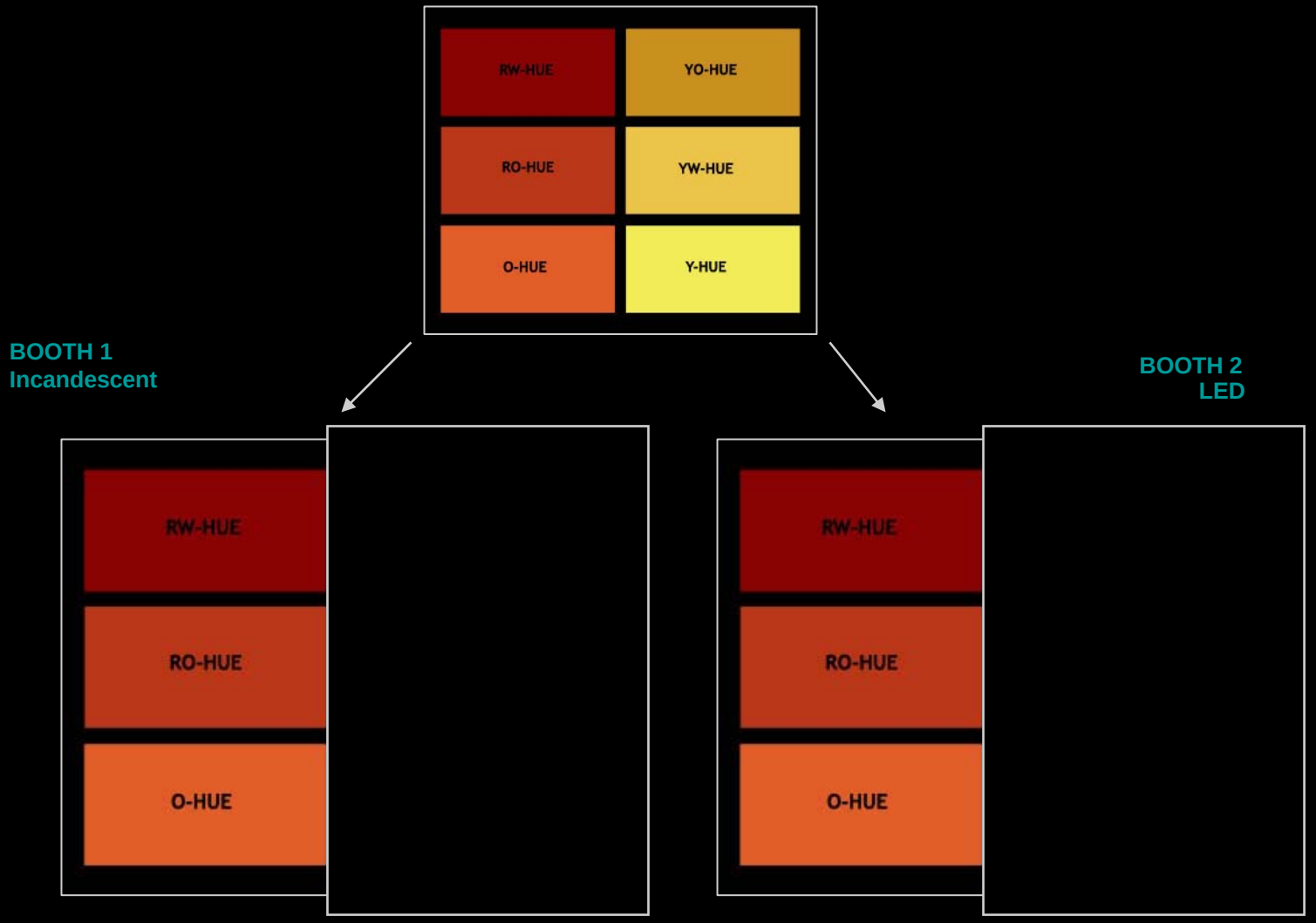
Selection from Color-Aid System



Phase 1 - Experiment Set-up - Color Samples



Phase 1 - Experiment Set-up - Color Samples

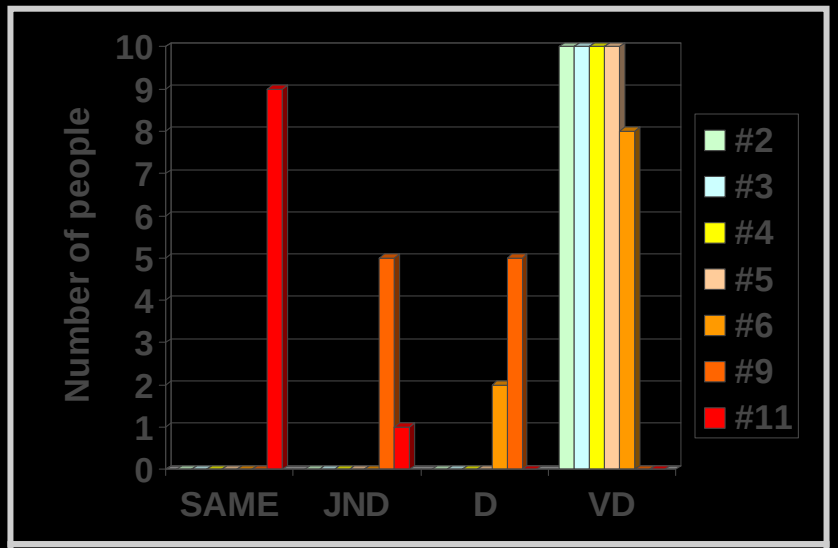


Results – Saturated RED Sample - PHASE 1A & 1B

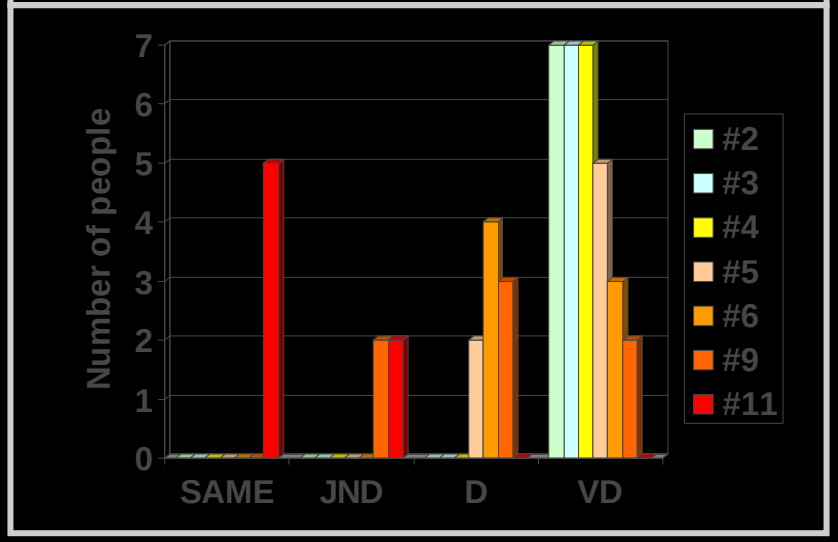
RW-HUE

Red-High saturation

1A



1B



Phase 1: Conclusions

Human Sensitivity to Color Rendering Discrete Modulation in LAB CONDITIONS :

- Saturation makes the difference. Perception of High saturation Red and Yellow samples showed strong association with changing CRI (rebalance of red and yellow energies).
- Color distortions were considered tolerable for a range of red samples of reduced saturation, including red toned skin color.
- Color distortions were less noticeable with sequential observation, confirming observations condition play a crucial role in perception of color distortions.

Phase 2 - Experiments

Baseline Experiments verified:

- CR modulation was mainly noticeable when looking at saturated reds samples.
- Reduction in sensitivity when the color changes were not seen side-by-side.

Main Goal for Phase 2:

- Substantiate previous results in the presence of context,
- Check eccentricity
- Check continuous modulation

Set-up:

- Subjects positioned at 0°, 10° & 20° from stimuli;
- Stimuli = colors in a realistic context, with prominent saturated red components;
- Modulation that is Continuous color rendering of RYGB LED white spectra

Experiments – Phase 2

Incandescent (fixed) LEDs (sequencing) Incandescent (fixed)

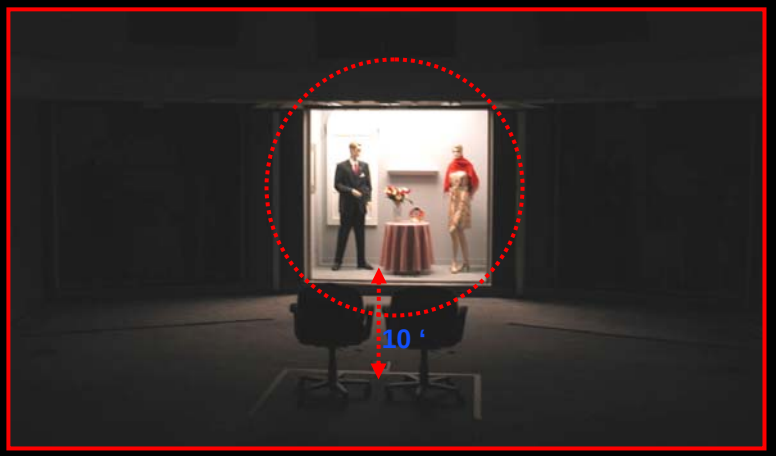
Experiments – Phase 2

Color temperature & Light Levels - Constant at 3,000 K & 260 lux
Color Rendering – Continuous automated Sequencing from Ra 92 to 34 (shifting slowly)

QUESTION: Did you notice any change in the appearance of either chamber?
If you did, when did you first notice the change?

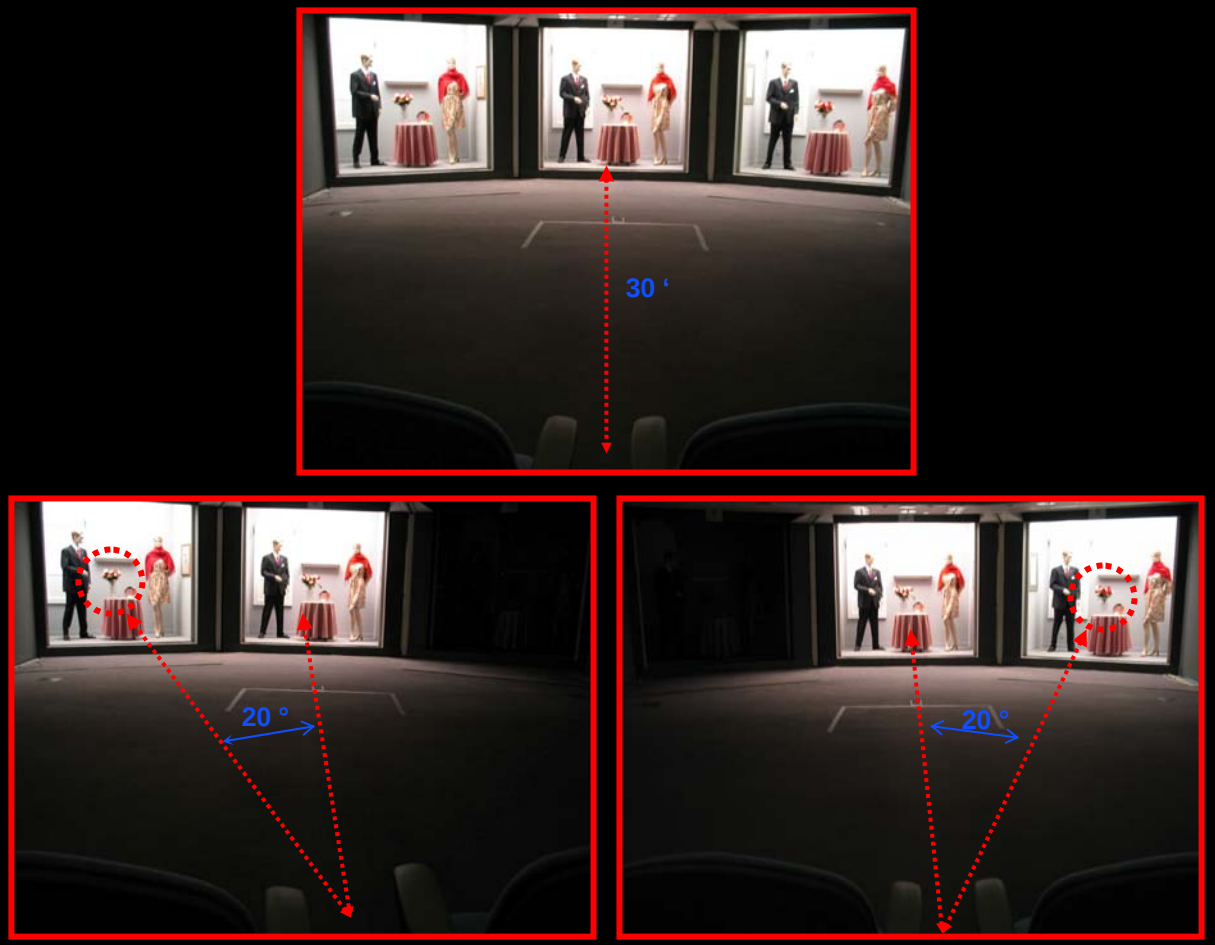
Experiments – Phase 2 – Experiments Design

0 DEGREE (FOVEAL VISION) TESTS - Direct observation of LED chamber



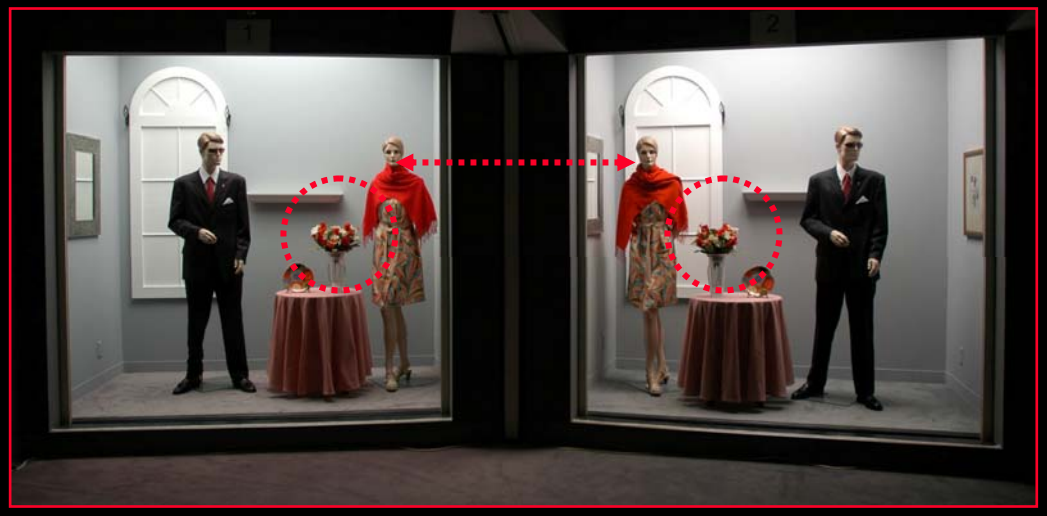
Experiments – Phase 2 – Experiments Design

20 DEGREE (PERIPHERAL) TESTS – Change Point at 20° (relative to center of gaze)

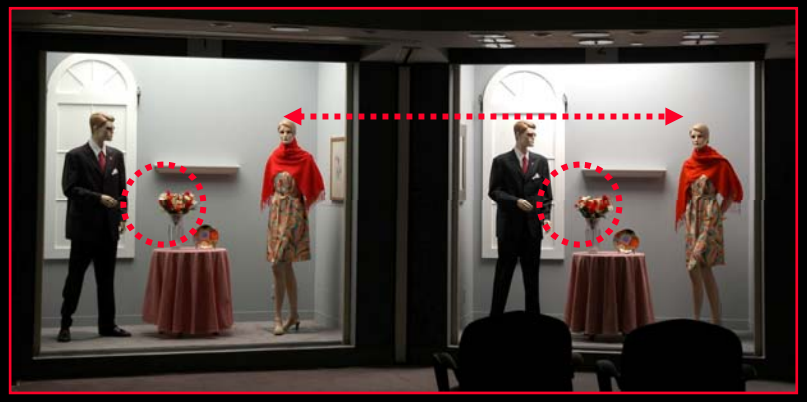


Experiments – Phase 2 - Experiments Design

10 DEGREE (OFF-CENTER) TESTS – Modified Layout for tightening of field of view and to allow change point to be located at 10° (relative to center of gaze).

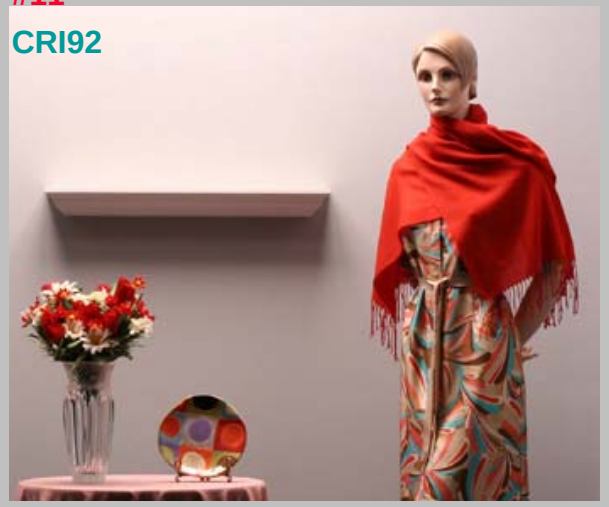


LAYOUT USED FOR 20 DEGREE TESTS



Phase 2 – Experiments – Sequencing of LED Spectra

#11
CRI92



09
CRI 79

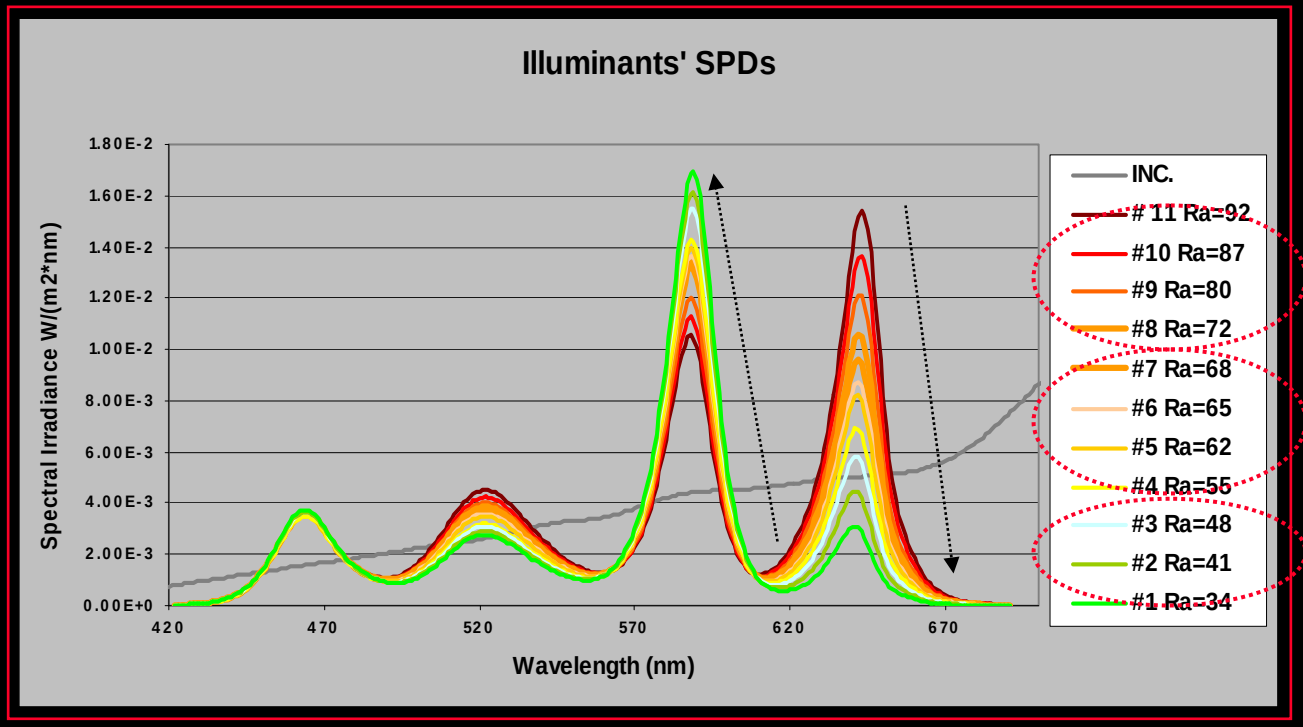
07
CRI 68

05
CRI 61

03
CRI 48

01
CRI 34

Experiments – Phase 2 – LED Spectra



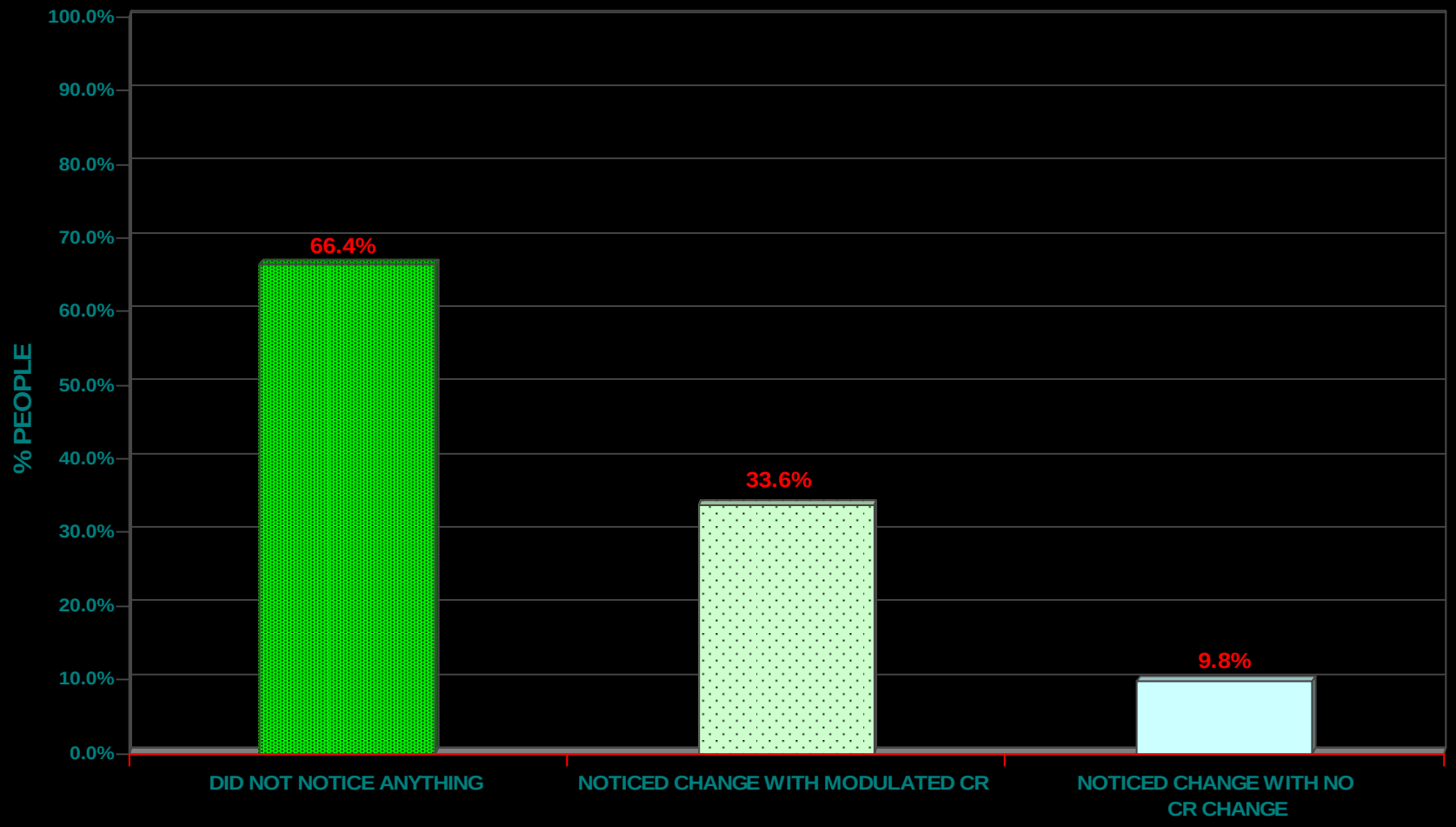
		HIGH CRI				MEDIUM CRI				LOW CRI		
	INC.	11	10	9	8	7	6	5	4	3	2	1
Lux	263	264	261	261	266	262	260	259	253	262	261	264
CCT (K)	3002	2966	2969	2970	2972	2976	2990	2981	2970	2952	2965	2975
CRI	98	92	87	80	72	68	65	62	55	48	41	34
LER lm/W*	273	312	323	334	347	354	362	366	374	386	398	410

*Theoretical Maximum LPW

Measurements conducted at Osram-Sylvania LRC, Dr. R. Levin, Joe Laski

Phase 2 - Experiments – RESULTS

QUESTION: DID PEOPLE NOTICE OUR CRI MODULATION?



Phase 2 - Experiments – RESULTS

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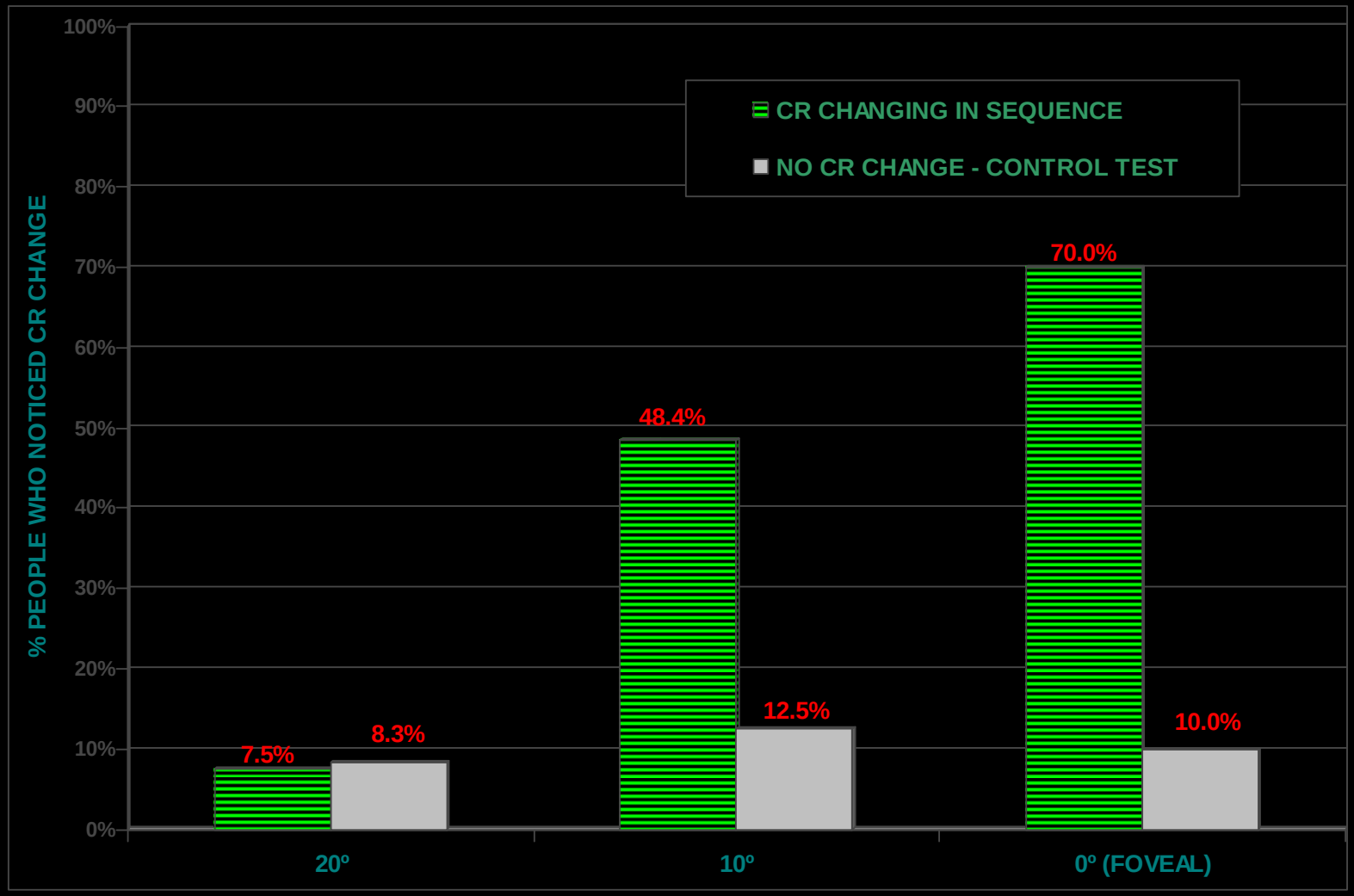
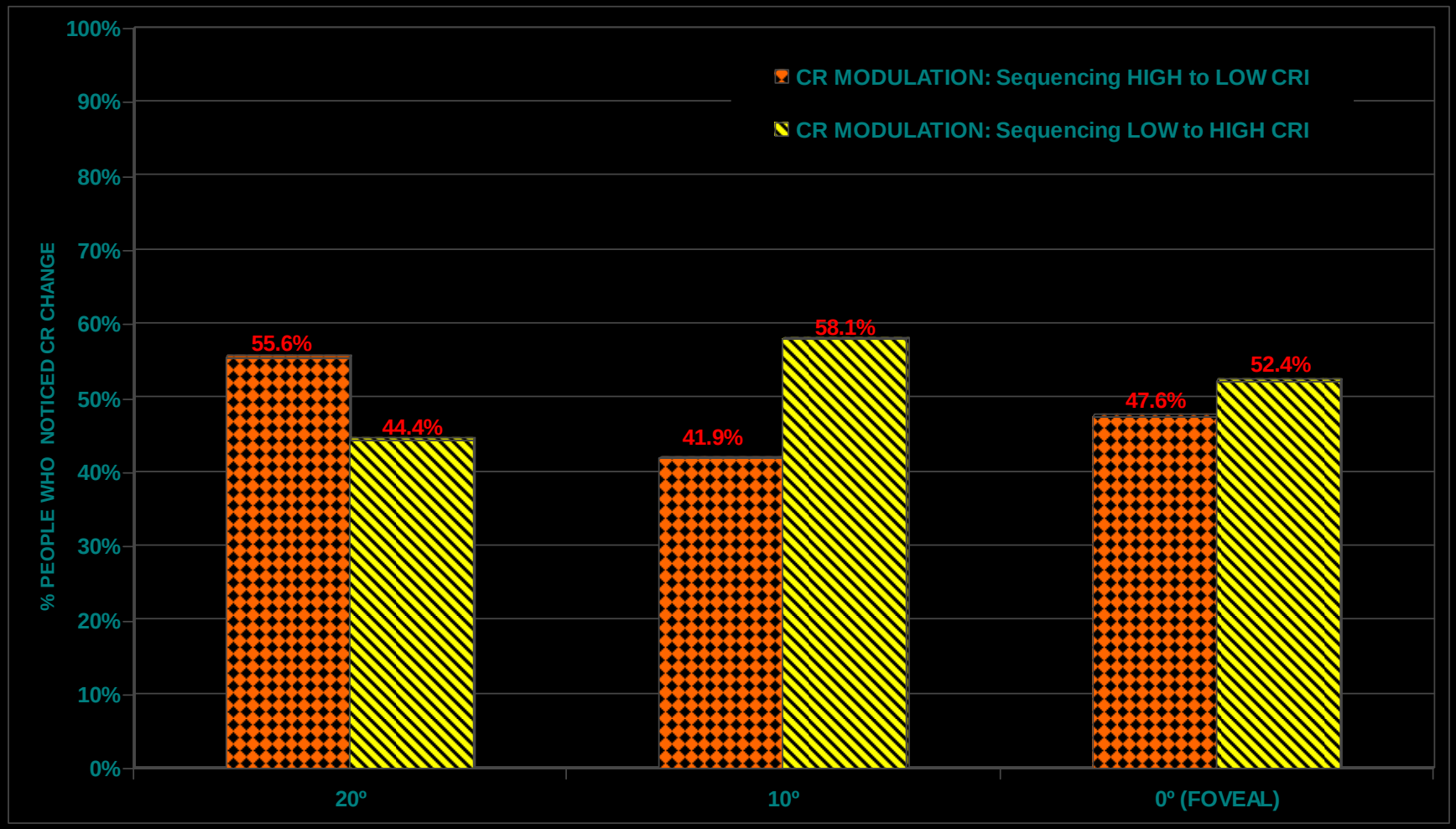
Q: FOR EACH DIRECTION OF GAZE, HOW MANY NOTICED A CHANGE?



Phase 2 - Experiments – RESULTS

Q: DOES IT MATTER IF WE SEQUENCE HIGH TO LOW OR LOW TO HIGH?



Experiments – Phase 2: CONCLUSIONS

Experiments represent worse case scenario:
- Lots of saturated red;
- Fix conditions (no consideration to attention span);
- Short time interval.

- Majority did not appreciably notice CR change.

- Perception CR change - strongly connected with direction of gaze [20°, 10° or 0°].

- At 10° changes more prominent than periphery, but still less than 50% noticed.

- Only at FOVEAL there was a significant difference if High, Middle or Low CRI.

- No significant difference for the two sequences of *Increasing* or *Decreasing* CR.

Color rendering rebalancing (via RYGB variation) will potentially be able to be finely controlled to match environmental features (i.e. surface colors and space activities).

What Does that Inform Lighting Practice?

Results encourage the thought that YES, CR modulation can potentially be made invisible during transitions from low CR mode to high CR mode and vice-versa.

Results strongly suggest that this is a viable control strategy to be pursued from the visual perception point of view.

- Lowest CRI range can be implemented comfortably at periphery (from 20° angle outwards).

- No lower than CRI 72 for partially occupied areas (from 10° angle inwards).

- Potential of strategy to be applied to partially occupied areas (10°) :
  - -Sparse saturated Red components;
  - -Longer rate of change

Implementation highly dependent on Range of Colors:

-Large open-area Office spaces – highly recommended.
-Retail with large colorful areas – potential for high proportions saturated red, lower reductions, lower gains.

- Rate of transition: 1 minute minimum rate. 2 minutes will probably work better.

Future Work - Research Plans

- **Planned Future Research:**
  - **Different angles for off center vision – How close can we go to foveal?**
  - **Different (longer) time intervals.**
  - **Different color schemes: hue and saturation variations. How much will colors impact? Lower saturation Reds? What if we had no red?**
  - **Isolated assessment for perception of luminance and color contrast.**
  - **Discrete Sequence of same LED Spectra – Will results persist?**
  - **More tests with various distances**
  - **Tests with Daylight component**

THANK YOU!

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