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S trange R things

The Melanopsin, Red Saturation, Brightness Connection

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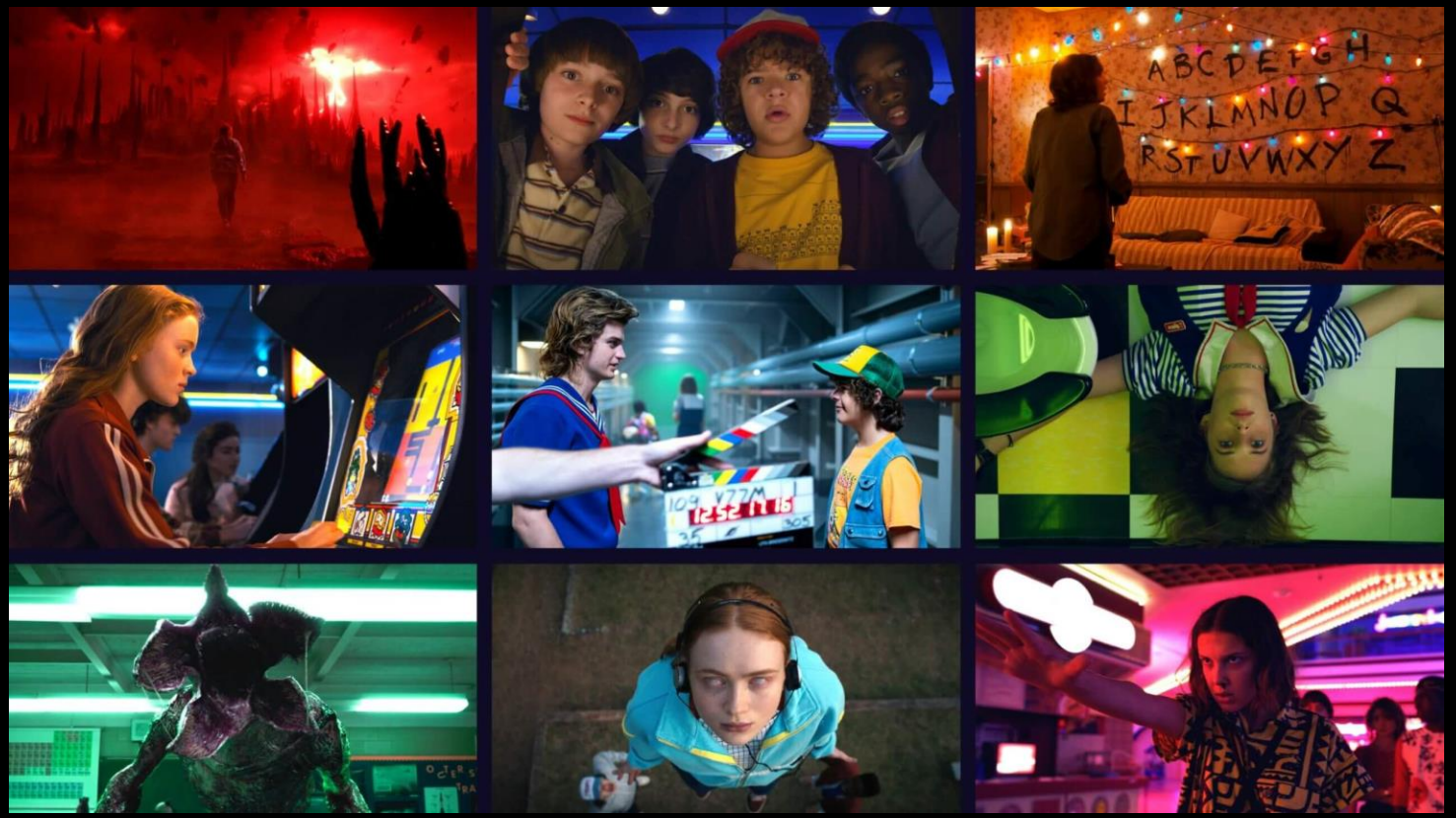
Learning Objectives

At the end of this course, participants will be able to:

1. explain the role of melanopsin in human brightness perception.
2. describe the impact of red saturation on perceived brightness.
3. analyze how color gamut can influence the effectiveness of lighting design.
4. apply these insights to optimize lighting environments for different use cases.

A group of researchers witness natural forces of lighting, color and perception.



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Starring: Mr. Clarke

https://screenrant.com/stranger-things-science-teacher-scott-clarke-hero-moments/

Dr. Alp Durmus

Assistant Professor

Penn State University

Research focus: lighting, color science, human factors, light pollution, NIF effects of light

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Storyline

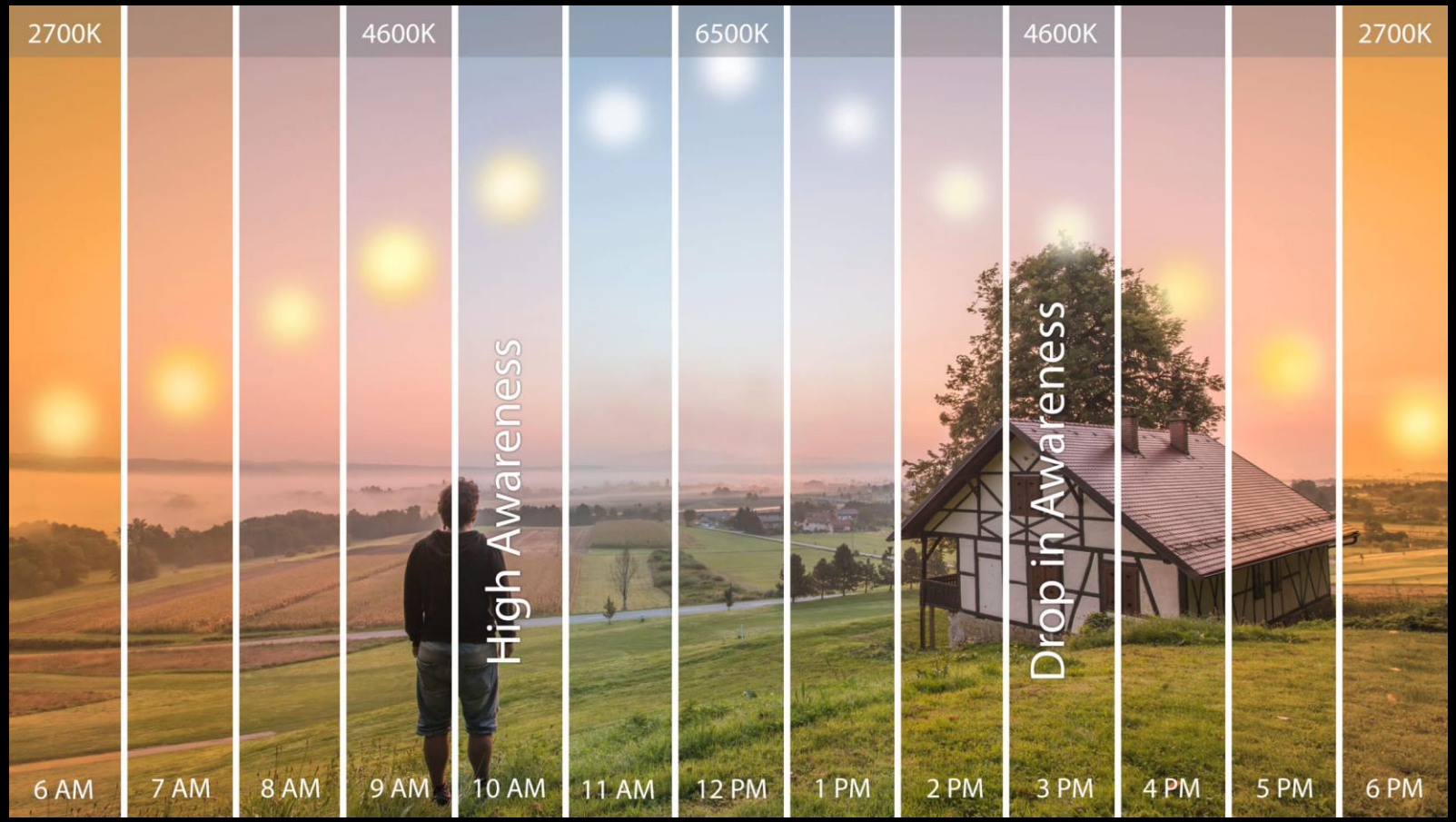
Visual and non-visual effects of Melanopsin

Subjective and perceptual effects of Color gamut

Combined effects of melanopsin and gamut on Brightness

chapter one
melanopsin

Circadian Rhythm and Lighting



https://www.thelightingpractice.com/what-is-circadian-lighting/

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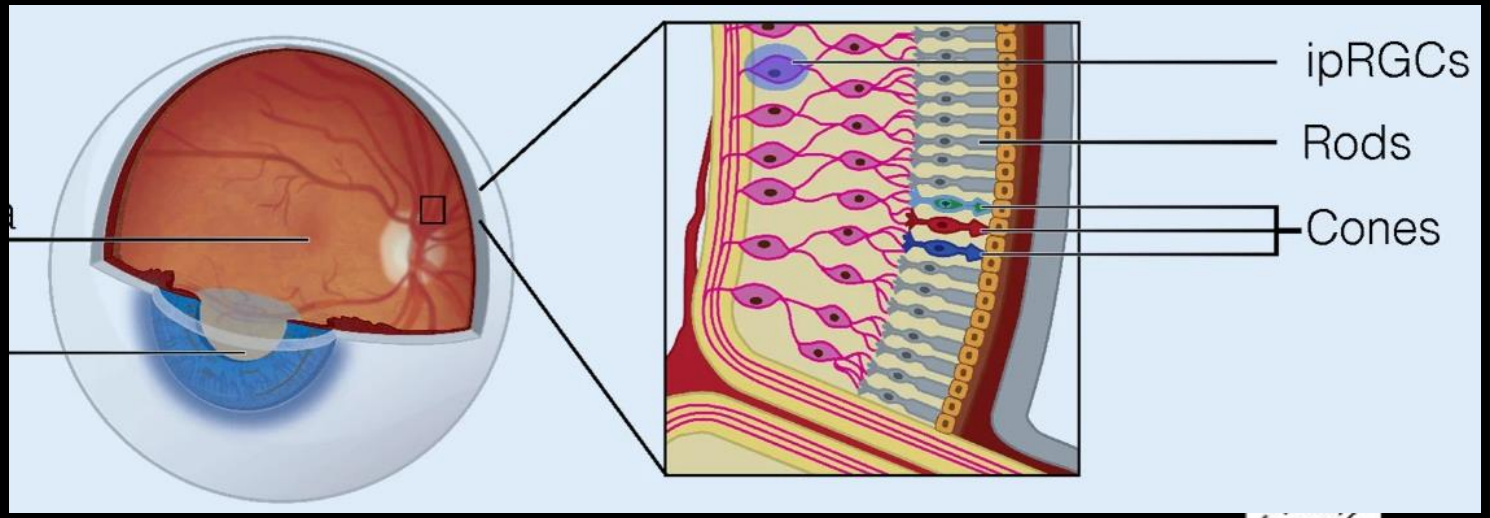
Melanopsin

Photopigment found in intrinsically photosensitive retinal ganglion cells (ipRGCs) in the retina
(Provencio et al., 2000; Hattar et al., 2002)

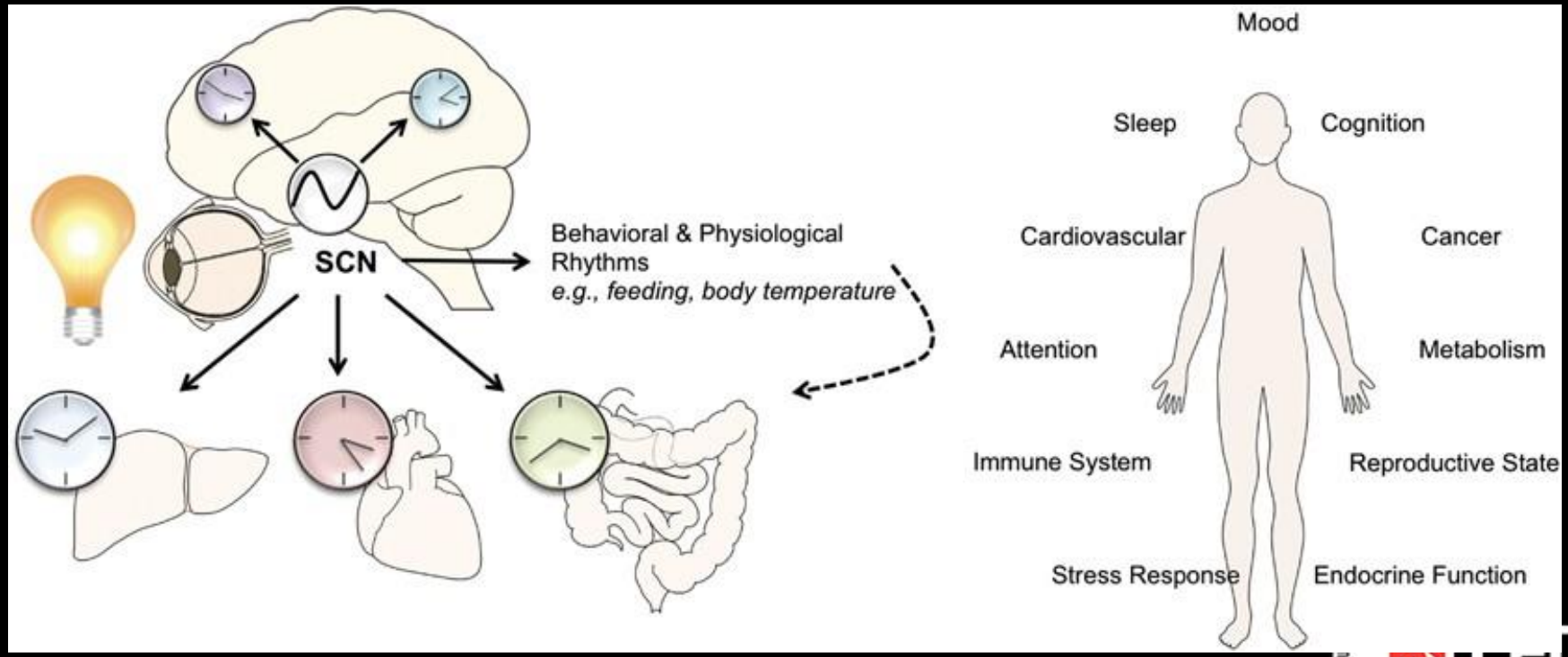
Adapts to dark-light (similar to rods and cones) but slower



]https://en.wikipedia.org/wiki/Intrinsically_photosensitive_retinal_ganglion_cell#/media/File:Overview_of_the_retina_photoreceptors_(a).png

Melanopsin and Human Body

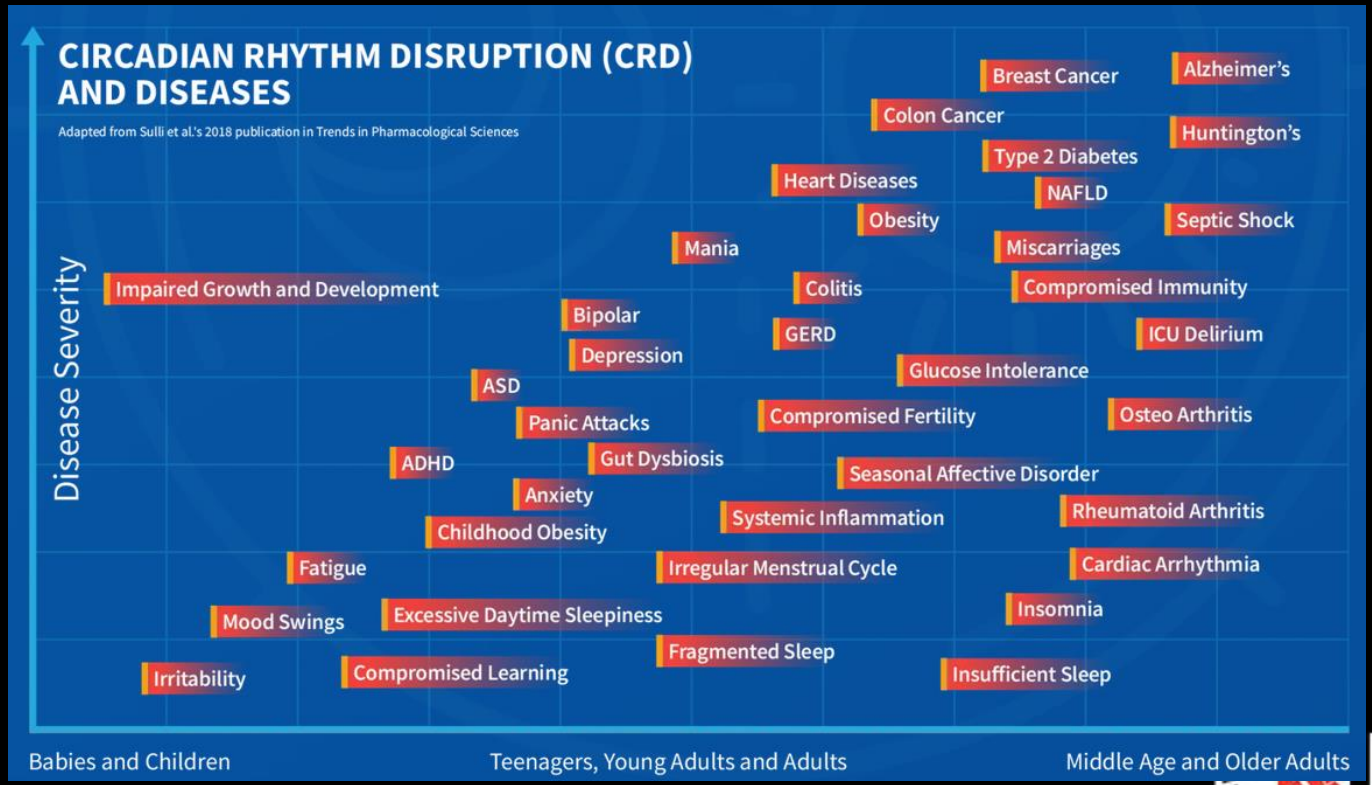
Contribute to reflexive responses of the brain and body (e.g., pupil dilation, melatonin release, heart rate, body temperature)
(Lucas et al., 2014)



https://www.nature.com/articles/tp2016262

Circadian Rhythm Disruption

Major influence on sleep quality, alertness, mood, learning, and even prostate or breast cancer. (Altimus et al., 2008; Cajochen et al., 2005; LeGates et al., 2012)



https://thecrdchallenge.com/

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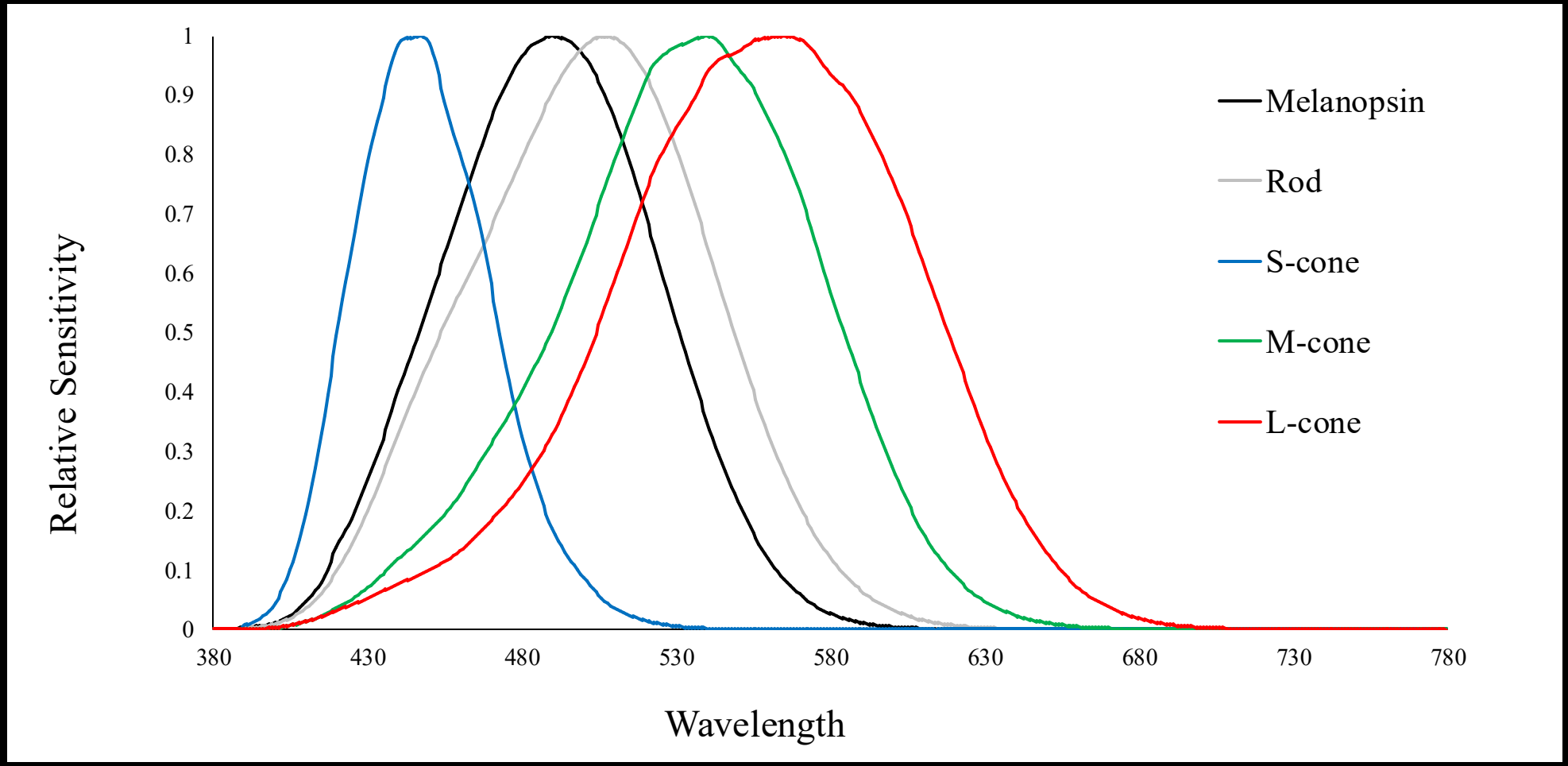
Spectral Sensitivity of Photoreceptors



Melanopic Equivalent Daylight Illuminance (mel-EDI)

Melanopic equivalent daylight illuminance ($E_{v,mel}^{D65}$, unit: lx)

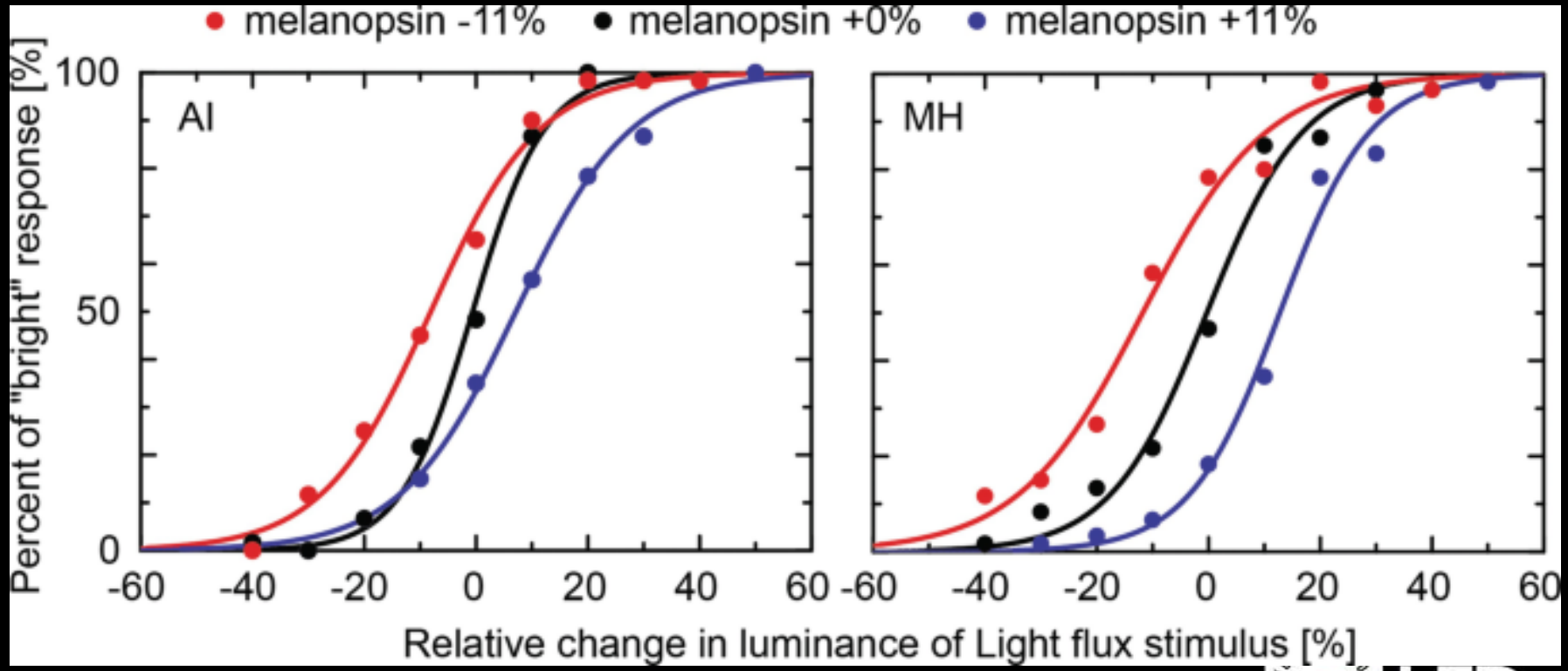
$$E_{v,mel}^{D65} = K_{v,mel}^{D65} \int_{380}^{780} E_e(\lambda)\, S_{mel}(\lambda)\, d\lambda$$

- $K_{v,mel}^{D65}$ is a constant (753.8 lm/ W)
- $S_{mel}(\lambda)$ is melanopsin sensitivity curve
- $E_e(\lambda)$ is is irradiance (W/m^2/nm)

Melanopsin Contribution to Brightness

Melanopsin was found to contribute to brightness perception in mice and humans.

(Brown et al., 2012; Zele et al., 2018; Yamakawa et al., 2019; DeLawyer et al., 2020; Zele et al., 2020)



Melanopsin Contribution to Brightness

Spatial brightness model with melanopsin fits better than models without melanopsin contribution. (Besenecker et al., 2016; Besenecker and Bullough, 2017)

$$B_2 = V(\lambda) + 0.6\,g\,S(\lambda) + 0.5\,Mel(\lambda)$$

Table 10 Prediction errors for the follow-up study. The reference condition is indicated in bold

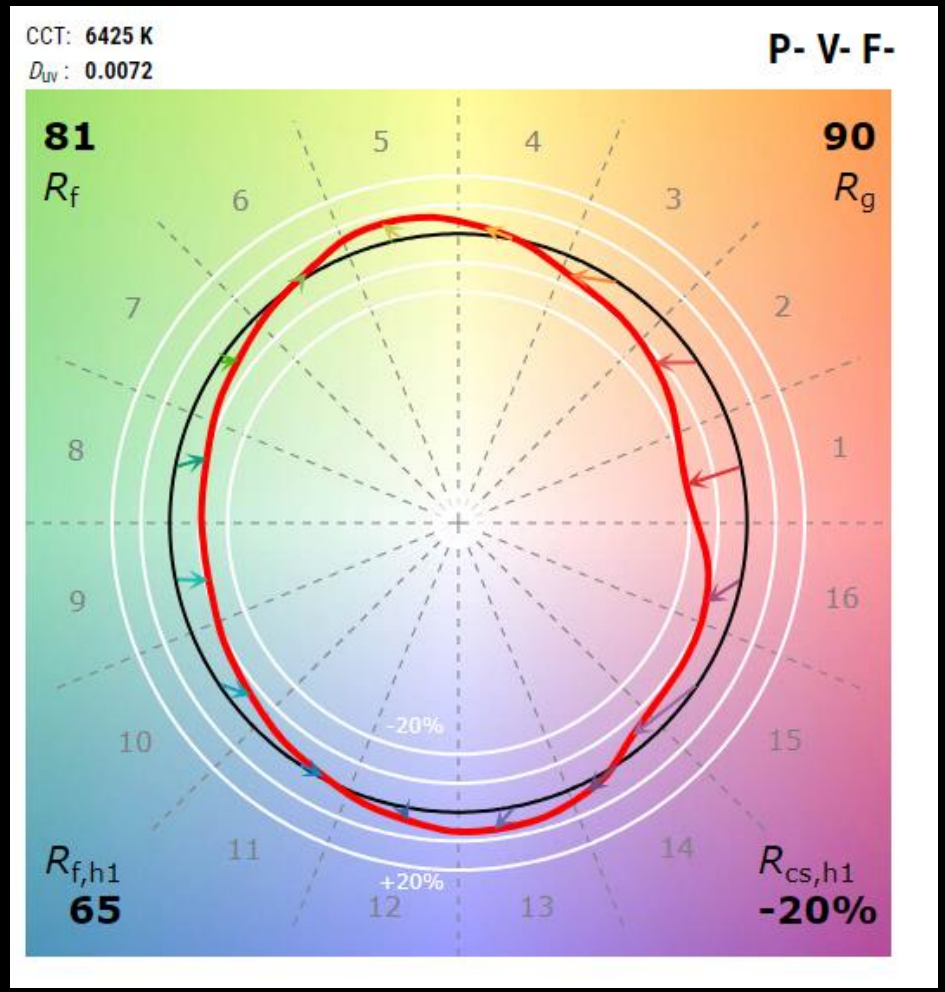
	Amber 1 SPD	Amber 2 SPD	Error (%)
Photopic Illuminance (lx)[5]	**50**	44	13.6
	52	**40**	23.1
Provisional Brightness B_1[25]	**51**	48	6.3
	53	**44**	17.0
Provisional Brightness B_2[33]	**52**	54	3.7
	54	**49**	9.3
Mesopic Photometry[35]	**50**	44	13.6
	52	**40**	23.1

chapter two

color gamut

ANSI/IES TM-30 Color Rendition

- Color fidelity index (R_f): light sources rendering ability of object colors compared to a reference illuminant. Higher values indicate better color fidelity.
- Gamut index (R_g): shift in average color saturation of the color samples under the test light source compared to a reference source. Higher values indicate higher average saturation.
- Chroma shift in hue bin 1 ($R_{cs,h1}$): negative values denote desaturation for red objects, and vice versa.



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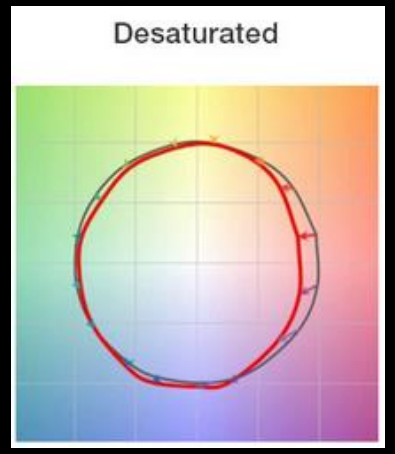
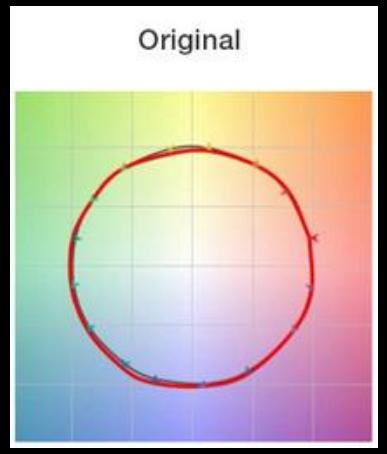
ANSI/IES TM-30 Color Gamut

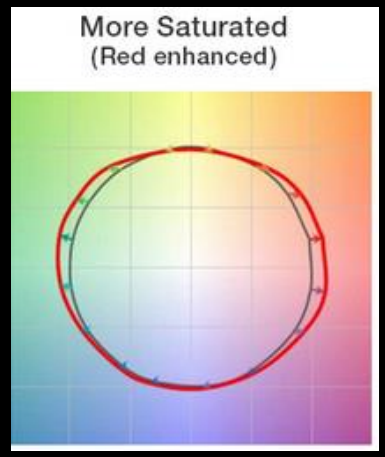
$R_g = 80$



$R_g = 100$



$R_g = 120$



https://hips.hearstapps.com/hmg-prod/images/stranger-things-season-3-1562418265.jpg

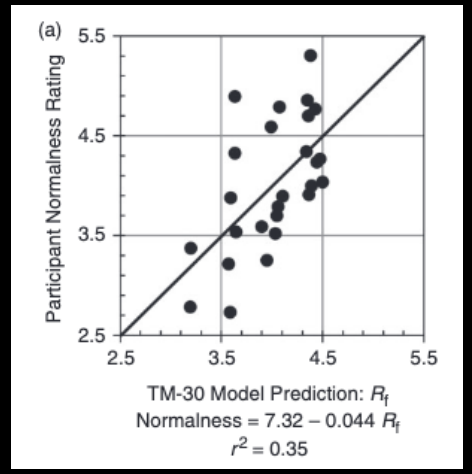
Limitations of Fidelity and Gamut

Fidelity metrics are not always good at predicting subjective ratings of "normalness," fidelity, or preference.

Table 3. Pearson Correlation Coefficients between the 20 CQ Metrics and the 3 CQ Attributes[a]

	IES R_f	R_g	$R_{cs,h1}$	R_a	CIE R_f	Q_a	Q_f	Q_p	Q_g	$R_{a,02}$
Naturalness	0.750*	0.408*	−0.036	0.659*	0.746*	0.752*	0.644*	0.669*	0.253*	0.724*
Colorfulness	−0.078	0.735*	0.919*	−0.289*	−0.079	0.011	−0.266*	0.686*	0.859*	−0.160
Preference	0.534*	0.651*	0.388*	0.369*	0.531*	0.573*	0.369*	0.811*	0.573*	0.476*
	$R_{a,12}$	RCRI	FCI	FCI02	FI	CPI	R_m	GAI	CDI	CSA
Naturalness	0.779*	0.615*	0.170	0.180	0.744*	0.545*	0.547*	0.091	0.091	0.038
Colorfulness	0.062	−0.242*	0.910*	0.938*	0.109	0.787*	0.621*	0.380*	0.380*	0.180
Preference	0.622*	0.351*	0.571*	0.582*	0.626*	0.787*	0.692*	0.177	0.177	0.037

[a]The asterisk denotes that the corresponding significance level (p value) is less than 0.01.



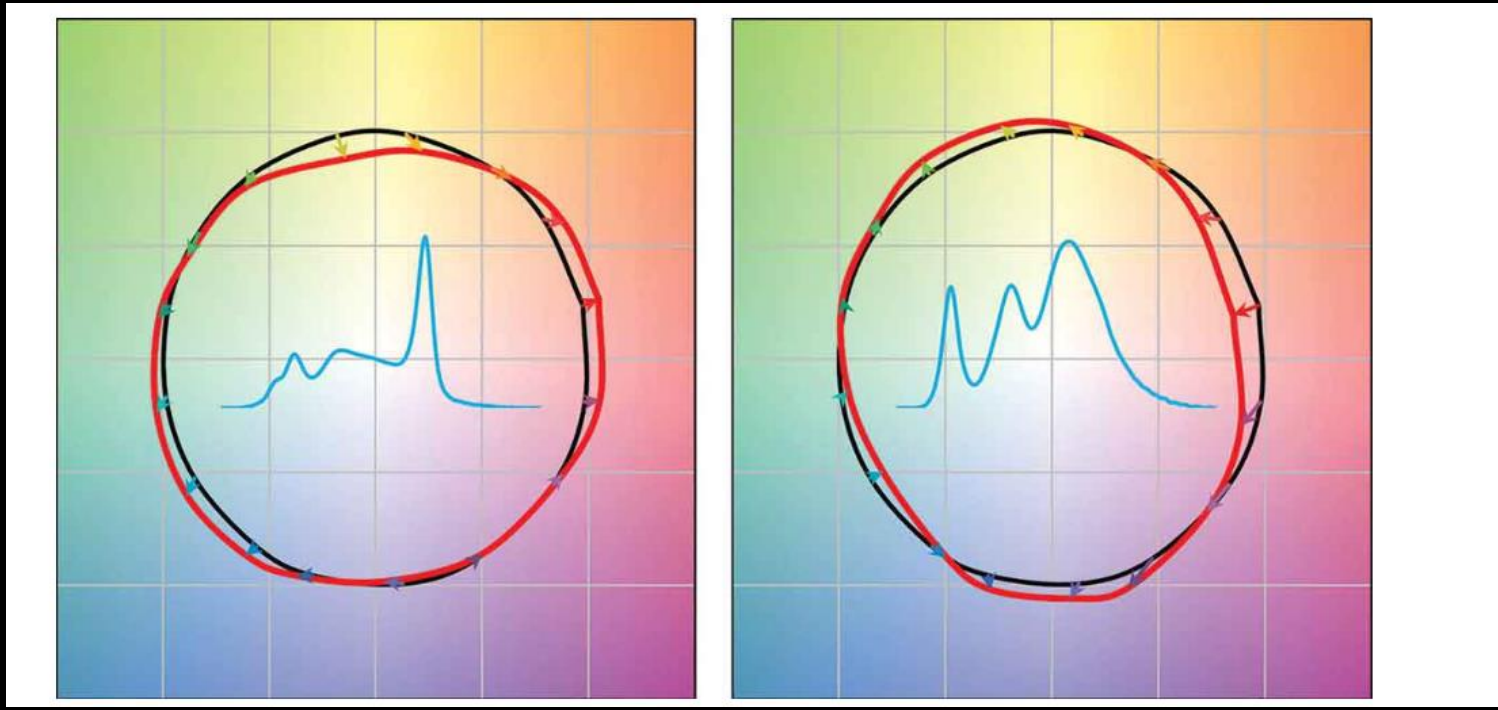
Zhang, F., Xu, H., & Feng, H. (2017). Toward a unified model for predicting color quality of light sources. *Applied Optics*, *56*(29), 8186-8195.

Royer, M. P., Wilkerson, A., Wei, M., Houser, K., & Davis, R. (2017). Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. *Lighting Research & Technology*, *49*(8), 966-991.

Limitations of Fidelity and Gamut

They provide only a partial understanding of color quality.

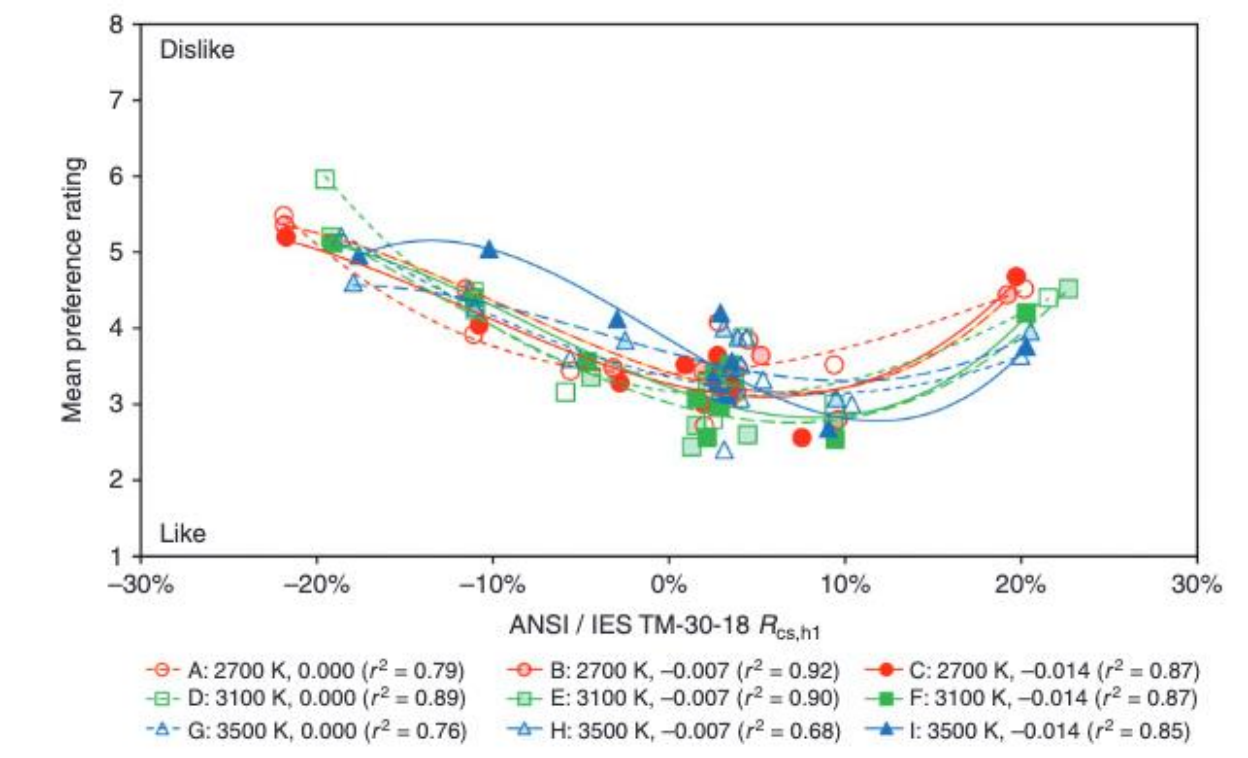
Similar gamut area ($R_g \approx 100$)

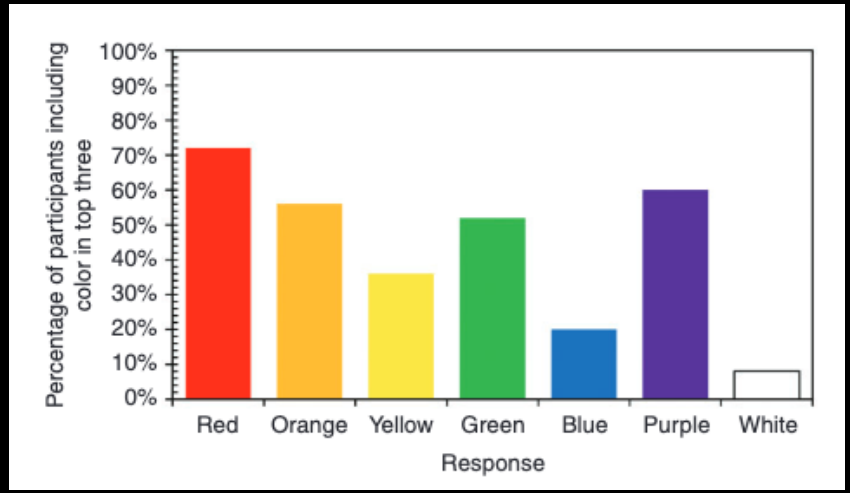


Saturated reds ($R_{cs,h1} > 0\%$) Desaturated reds ($R_{cs,h1} < 0\%$)

Royer, M. P., Houser, K. W., & David, A. (2018). Chroma shift and gamut shape: going beyond average color fidelity and gamutarea. Leukos, 14(3), 149-165.

Red Saturation and Preference





Royer, M. P., Wei, M., Wilkerson, A., & Safranek, S. (2020). Experimental validation of colour rendition specification criteria based on ANSI/IES TM-30-18. *Lighting Research & Technology*, *52*(3), 323-349.

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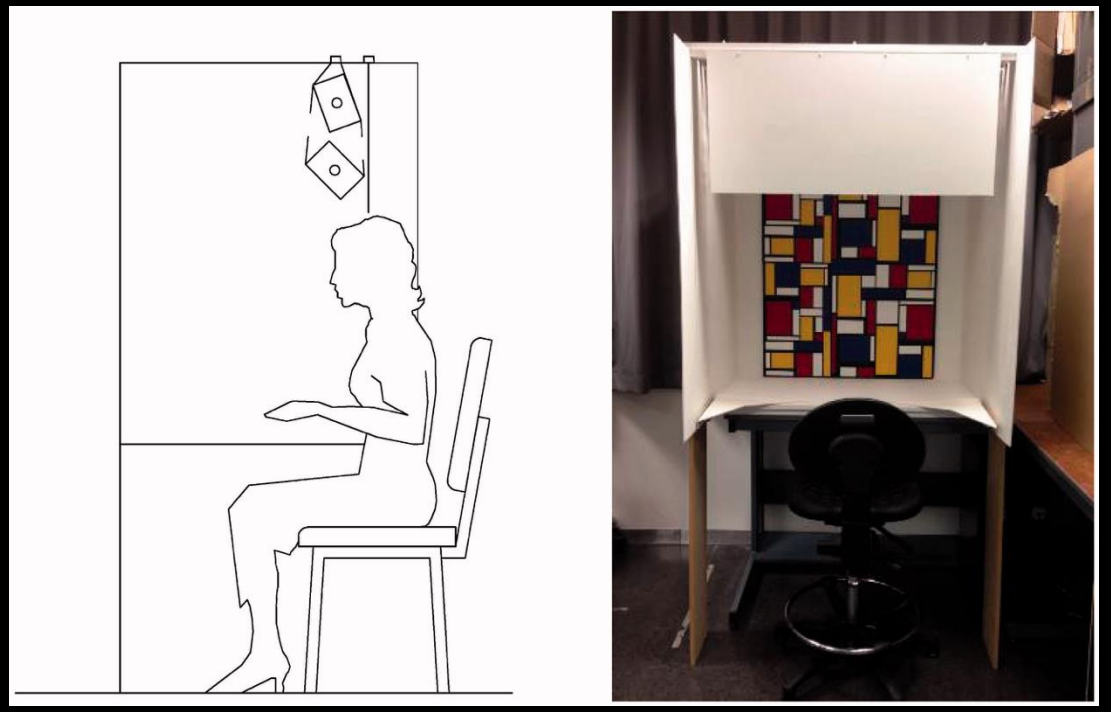
Gamut Contribution To Brightness

Higher gamut light sources were perceived brighter compared to lower gamut.
(Fotios and Cheal, 2011) (Fotios et al., 2015)



Fotios, S., Atli, D., Cheal, C., & Hara, N. (2015). Lamp spectrum and spatial brightness at photopic levels: Investigating prediction using S/P ratio and gamut area. Lighting Research & Technology, 47(5), 595-612.

Fotios, S. A., & Cheal, C. (2011). Predicting lamp spectrum effects at mesopic levels. Part 1: Spatial brightness. Lighting Research & Technology, 43(2), 143-157.

chapter three

melanopsin, gamut & brightness

Study 1: Royer et al.

Royer, M., Abboushi, B., & Bermudez, E. R. F. (2024) Relative Contributions of Sc-DER, Mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception. *Mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception*.

https://getyarn.io/yarn-clip/dd0e97a8-6559-4749-8e98-be8c2f4b7783

Study 1: Methods

Table 2. Nominal targets for the eight different color rendition conditions.

Condition	R_f	R_g	$R_{cs,h1}$	Orientation
A	80	100	−12%	Blue-Yellow
B	80	100	−7%	Blue-Yellow
C	80	100	10%	Red-Green
D	80	94	2%	Red-Green
E	80	110	2%	Blue-Yellow
F	80	110	10%	Neutral
G	90	100	2%	Neutral
H	80	94	−12%	Blue-Yellow

Fig. 2. Photograph of the experiment room from the participants' perspective.

Royer, M., Abboushi, B., & Bermudez, E. R. F. (2025) Relative Contributions of Sc-DER, Mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception. *Mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception*. LEUKOS.

Study 1: Results

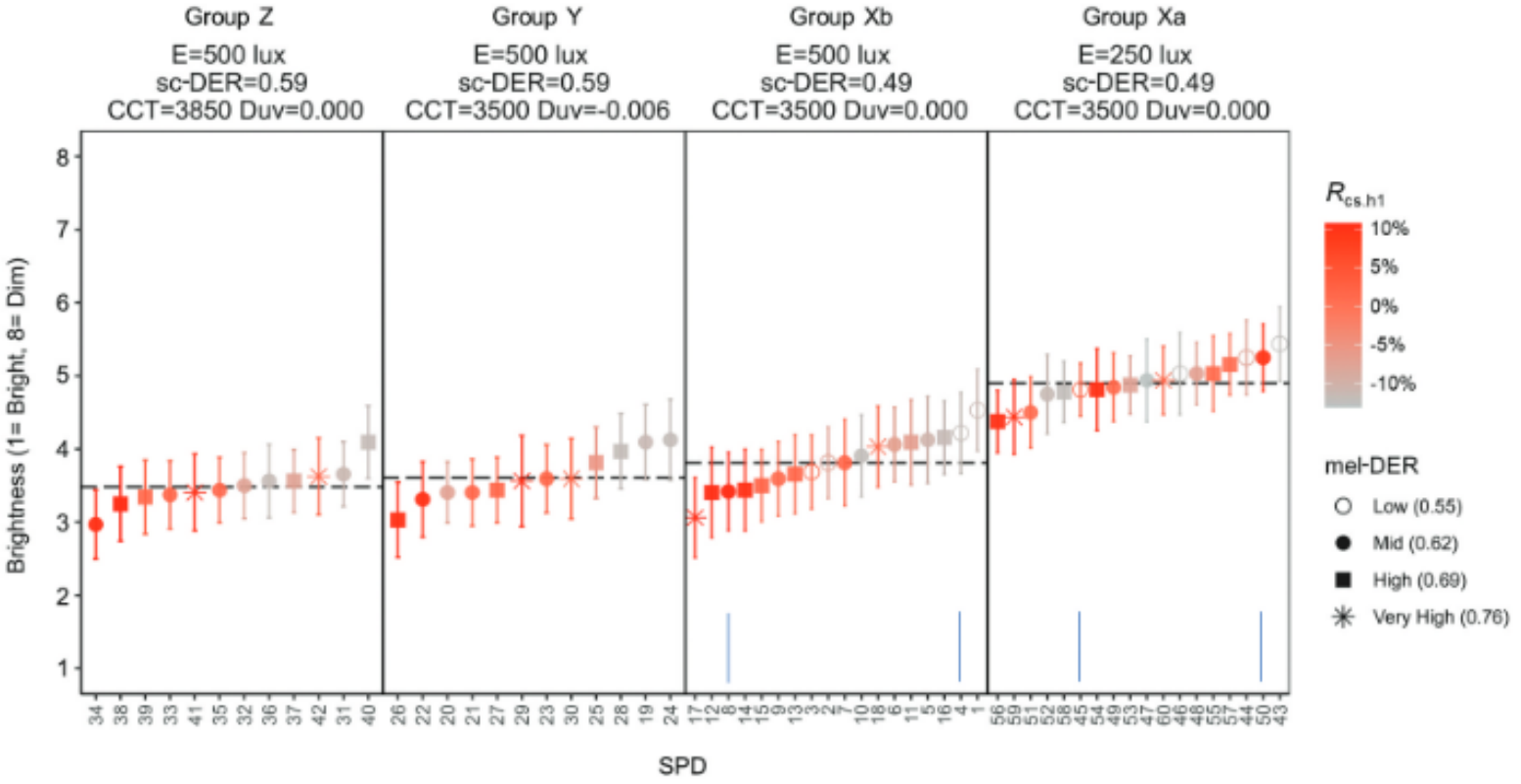


Fig. 5. Mean brightness ratings and 95% confidence intervals for all 60 evaluated conditions. The dashed lines represent the mean for the group.

Royer, M., Abboushi, B., & Bermudez, E. R. F. (2025) Relative Contributions of Sc-DER, Mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception. *Mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception*. LEUKOS.

Study 1: Results

Table 7. *P* value of predictors for the four remaining dependent variables (warm-cool, natural-distorted, vibrant-dull, and like-dislike). The $R_{cs,h1}$:Eh(nom) interaction was not significant for any dependent measure and thus was removed from the models.

	Warm–Cool	Natural–Distorted	Vibrant–Dull	Like – Dislike
E_h(nom)	0.005**	<0.001**	<0.001**	<0.001**
sc-DER	<0.001**	0.387	0.864	0.387
mel-DER	0.456	0.539	0.110	0.413
R_f	0.883	<0.001**	0.806	0.015*
R_g	0.002**	<0.001**	0.769	0.003**
$R_{cs,h1}$	0.763	0.023	<0.001**	0.602
CCT	0.001**	0.226	0.507	0.253
Duv	<0.001**	0.667	0.363	0.331
$R_{cs,h1}^2$	–	–	–	<0.001**
$R_{cs,h1}^2$:E_h(nom)	–	–	–	0.032*

* and ** denote significance at the $\alpha \leq 0.05$ and $\alpha \leq 0.01$ levels, respectively. Note: R_{csh1} squared is used to account for quadratic relationship.

Royer, M., Abboushi, B., & Bermudez, E. R. F. (2025) Relative Contributions of Sc-DER, Mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception. *Mel-DER, Color Rendition, Chromaticity, and Illuminance to Spatial Brightness Perception*. LEUKOS.

Study 1: Results

Summary of findings:

- Illuminance had the largest effect on brightness perception.
- Second largest effect was due to changes in red chroma ($R_{cs,h1}$)
- The effects of melanopsin and CCT were not statistically significant.

Study 2: Song and Durmus

Hypotheses

Part 1

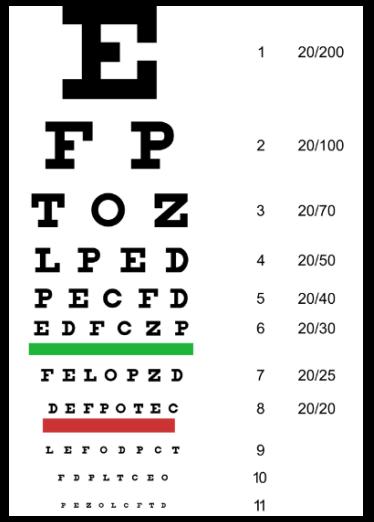
- Melanopic equivalent daylight illuminance (mel-EDI) can predict spatial brightness.

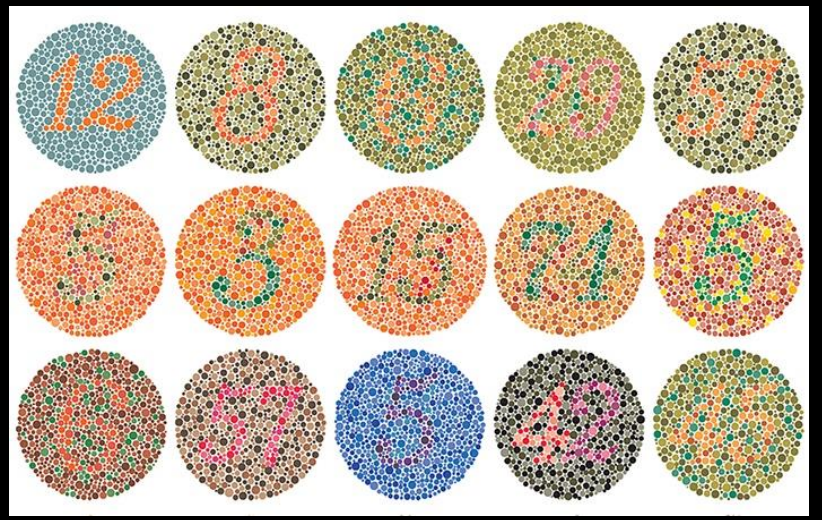
Part 2

- Gamut area (R_g) and chroma shift of hue bin 1 ($R_{cs,h1}$) both impact spatial brightness.

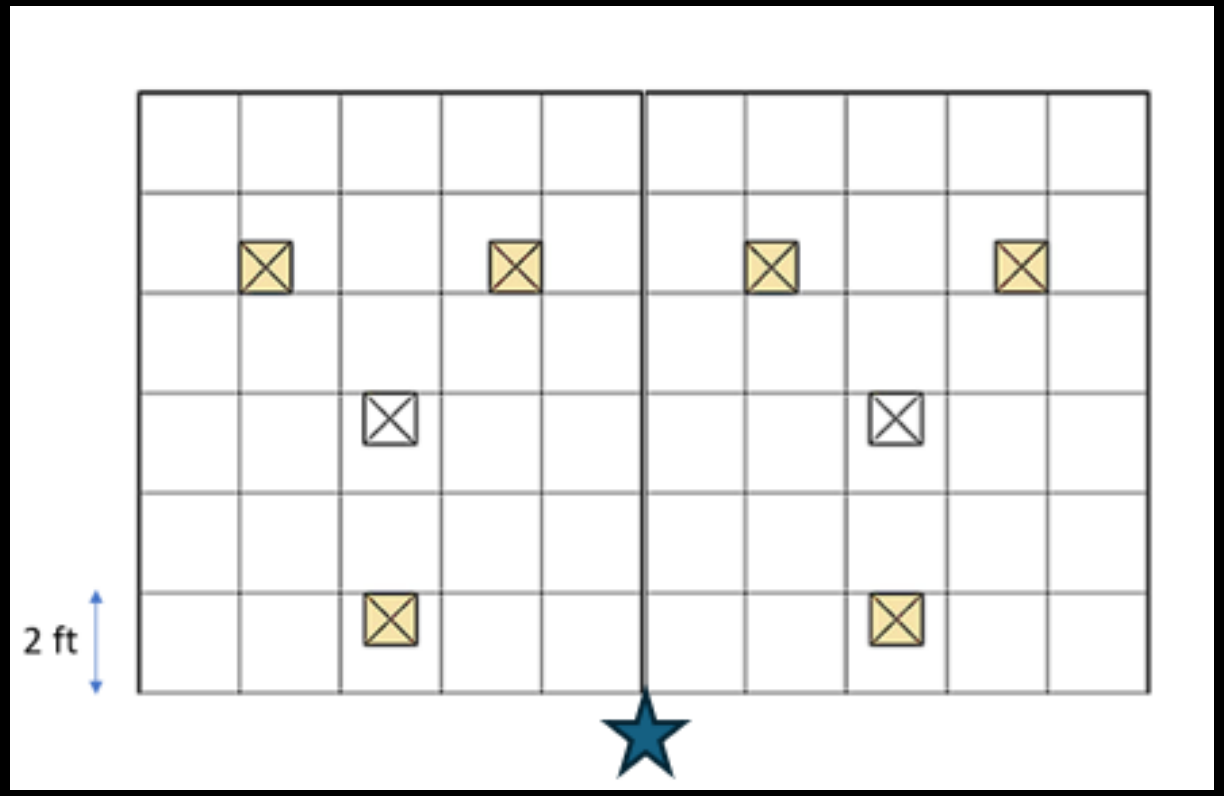
Study 2: Methods

- 42 Participants (20 male and 22 female)
- Average age = 26. Ages ranged from 19 to 51.
- Good visual acuity
- Normal color vision
- IRB approved.
- Training was provided.





Study 2: Methods



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Study 2: Methods

Side-by-side 2 alternative forced choice (2AFC) method

Study 2: Lighting Conditions (Part 1)

2 CCTs at 2 illuminance levels

120 lx	40 lx	75 lx	40 lx
2800 K		4700 K	

Part 1								
	Pair 1		Pair 2		Pair 3		Pair 4	
	pcLED	mcLED	pcLED	mcLED	pcLED	mcLED	pcLED	mcLED
E_v (lx)	120.1	120	40	39.6	75.1	74.9	40	39.8
mel-EDI (lx)	48.1	57.7	15.7	19	39.30	44.2	20.50	25.8
CCT (K)	2799	2787	2771	2791	4741	4722	4688	4719
u'	0.2579	0.2589	0.2589	0.2583	0.2061	0.2064	0.2061	0.2057
v'	0.5268	0.525	0.5286	0.5269	0.5022	0.5024	0.5044	0.5037
CRI R_a	81.9	82.4	82.4	80.8	63.8	72.9	63.3	76.5
R_f	84	84.2	84.7	83.6	66.2	65.1	66.20	65.7
R_g	97.3	97.1	97.1	95.4	94.3	95.2	93.90	93.8
Duv	0.001	0.0004	0.0019	0.001	0.0122	0.0121	0.0133	0.0132
R_{csh1}	-10.5	-13	-10.5	-12.1	-18.5	-19	-18.5	-20.1

Study 2: Results (Part 1)

2800 K

- Lower illuminance: nope!
- Medium illuminance: reverse!!

4750 K

- Lower and higher illuminance: melanopsin predicts

https://giphy.com/gifs/sagawards-reaction-confused-26xBDMWQLwRgrRJcs

Study 2: Lighting Conditions (Part 2)

Part 2									
	Ref	S1	S2	S3	S4	S5	S6	S7	S8
E_v (lx)	40.1	40.0	39.8	40.3	40.1	40.0	39.7	40.0	40.0
mel-EDI (lx)	31.1	31.3	31.0	30.7	30.9	30.7	31.3	30.7	30.9
CCT (K)	4724	4610	4782	4766	4669	4645	4625	4894	4668
Duv	0.0102	0.0088	0.0084	0.0112	0.010	0.012	0.009	0.011	0.0102
u'	0.2077	0.2108	0.2082	0.207	0.210	0.207	0.210	0.205	0.208
v'	0.5002	0.4996	0.4972	0.504	0.503	0.504	0.500	0.498	0.501
CRI R_a	95.6	89.2	91.6	85.7	90.7	87.7	91.8	92.8	84.3
R_f	96.6	88.1	90.8	84.8	89.1	88.6	91.2	90.8	89.5
R_g	97.9	98.9	96.8	108.9	91.5	106.7	93.8	101.7	88.8
R_{cshl}	0	10	-11	0	0	10	3	-5	-10

- S1- Higher $R_{cs,h1}$
- S2- Lower $R_{cs,h1}$
- S3- Higher R_g
- S4- Lower R_g
- S5- Higher R_g, higher $R_{cs,h1}$
- S6- Lower R_g, higher $R_{cs,h1}$
- S7- Higher R_g, lower $R_{cs,h1}$
- S8- Lower R_g, lower $R_{cs,h1}$

- 8 stimulus created compared with Ref.
- Red—Higher, green—lower than Ref.

Study 2: Results (Part 2)

- S1- Higher $R_{cs,h1}$
- S2- Lower $R_{cs,h1}$
- S3- Higher R_g
- S4- Lower R_g
- S5- Higher R_g, higher $R_{cs,h1}$
- S6- Lower R_g, higher $R_{cs,h1}$
- S7- Higher R_g, lower $R_{cs,h1}$
- S8- Lower R_g, lower $R_{cs,h1}$

S1,S2: Lower $R_{cs,h1}$ brighter.

S3,S4: Higher R_g brighter.

S5,S6,S7: Lower $R_{cs,h1}$ + higher R_g brighter.

S8: Lower $R_{cs,h1}$ + lower R_g brighter (!)

Study 2: Results

Summary of findings:

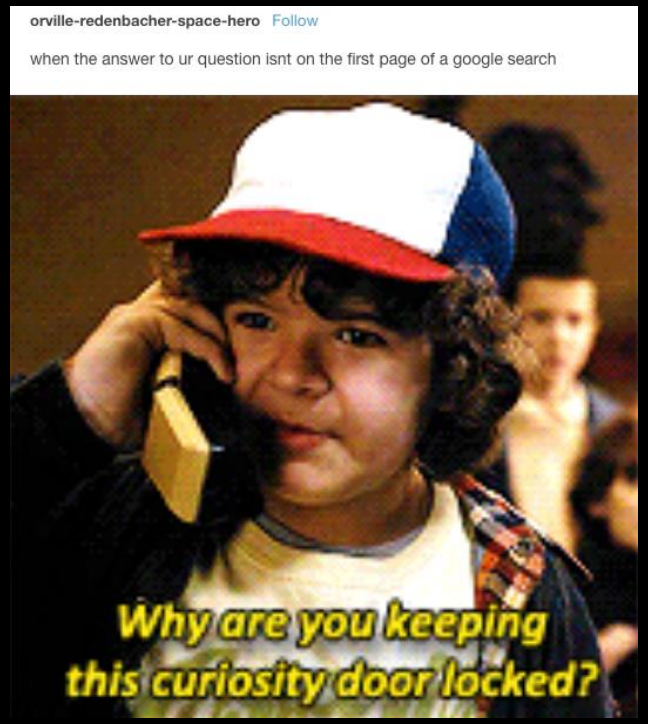
- Mel-EDI could only predict spatial brightness under lower CCT lighting conditions.
- Lower $R_{cs,h1}$ (desaturated red) and higher R_g (average increased gamut) were perceived brighter, which partially conflict with Royer et al. findings.
- Objects and experimental protocol might explain the differences between study 1 and 2.

Plot Summary

- Melanopsin only partially impacts spatial brightness.
- Color gamut, especially increase in red color, somehow impacts brightness perception of spaces with and without objects.
- $R_{cs,h1}$ and R_g together can help predict spatial brightness.

Spin-offs?

- We should investigate the effect of age, wider range of CCT and illuminance levels.
- Adaptation duration and field of view can be further investigated.
- We need theories to test the underlying mechanisms.



https://screenrant.com/wp-content/uploads/2017/10/stranger-things-meme2.png

Key Takeaways

- Color rendering index (CRI) is outdated and incomplete. Avoid like the plague!

- Designers should
  - Request TM-30 data, especially CVG, $R_{cs,h1}$ and R_g
  - Follow CIE guidance using mel-EDI levels where possible

- Manufacturers should
  - Provide TM-30 data, especially CVG, $R_{cs,h1}$ and R_g
  - IES has a free TM-30 online calculator: https://www.ies.org/standards/standards-toolbox/tm-30-spectral-calculator/

Credits

Data Collection and Analysis

WANYANG SONG

Funding

INSTITUTE OF ENERGY AND THE ENVIRONMENT (IEE)

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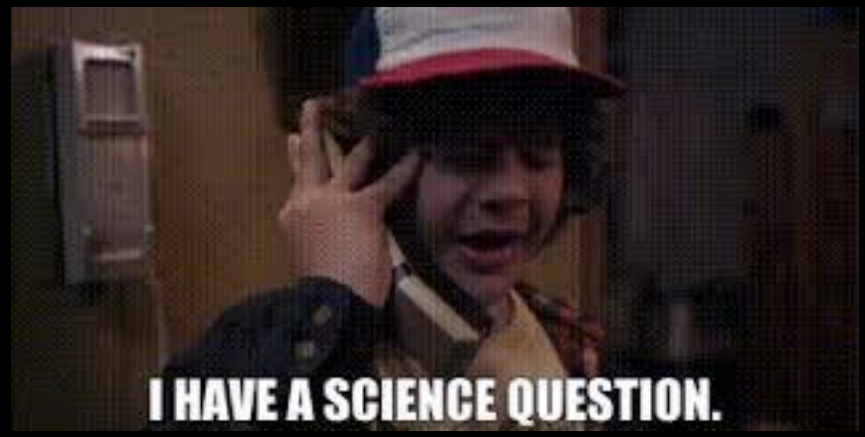
The end!



https://music.getyarn.io/yarn-clip/5885084e-7356-4290-bfe9-81717717360e/gif

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This concludes The American Institute of Architects Continuing Education Systems Course

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Thank you for attending!

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