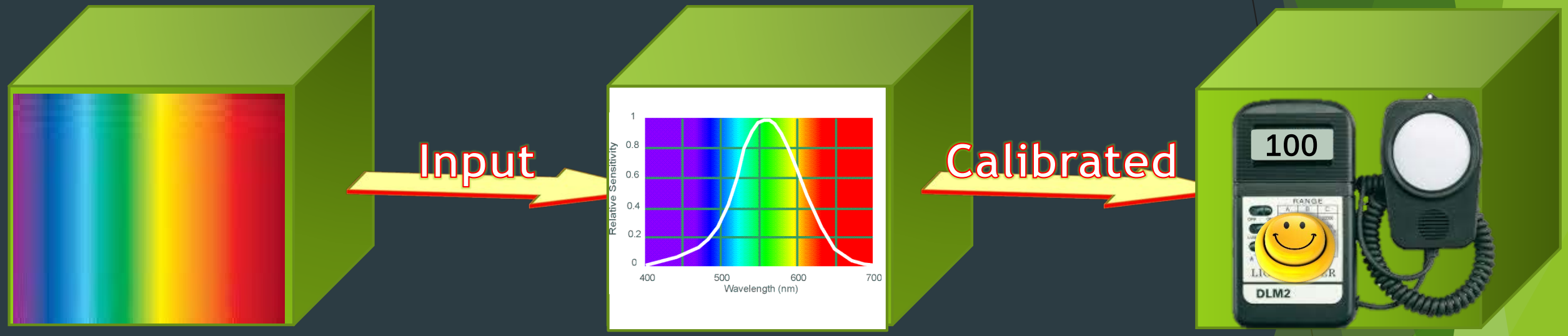
Melanopsin, True Brightness, and the Recalibration of Light Meters

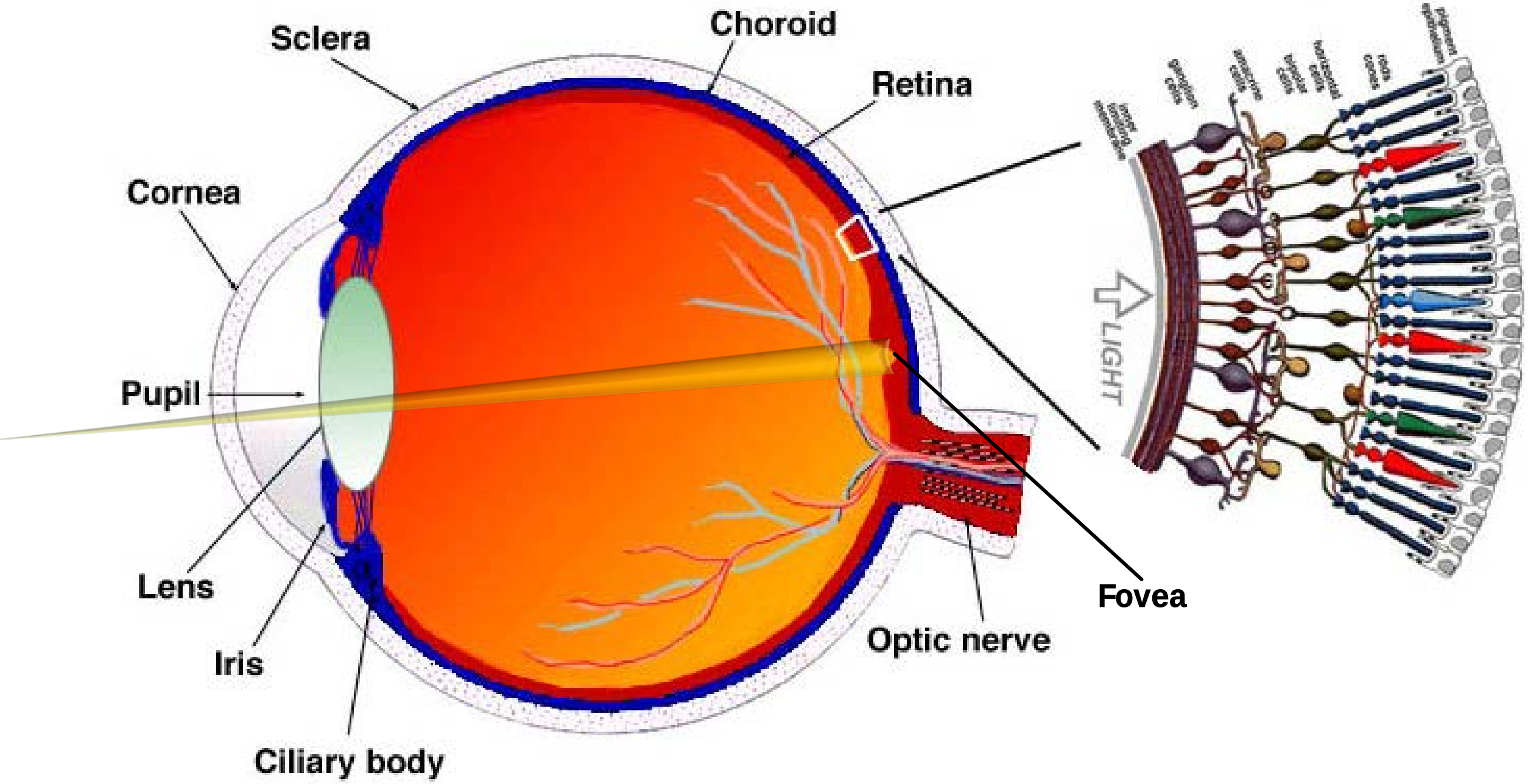
Bradley Schlesselman, Myron Gordin, Larry Boxler[1], Jason Schutz, Sam Berman[2], Brian Liebel[2] and Robert Clear[2]

Musco Sports Lighting, LLC, 100 1st Avenue West, Oskaloosa, Iowa 52577

1. Former employee, 2. Consultant

Some Background on Light Meters and Brightness Perception


Input
Relative Sensitivity
1
0.8
0.6
0.4
0.2
0
400
500
600
700
Wavelength (nm)
Calibrated
100
RANGE
DLM2

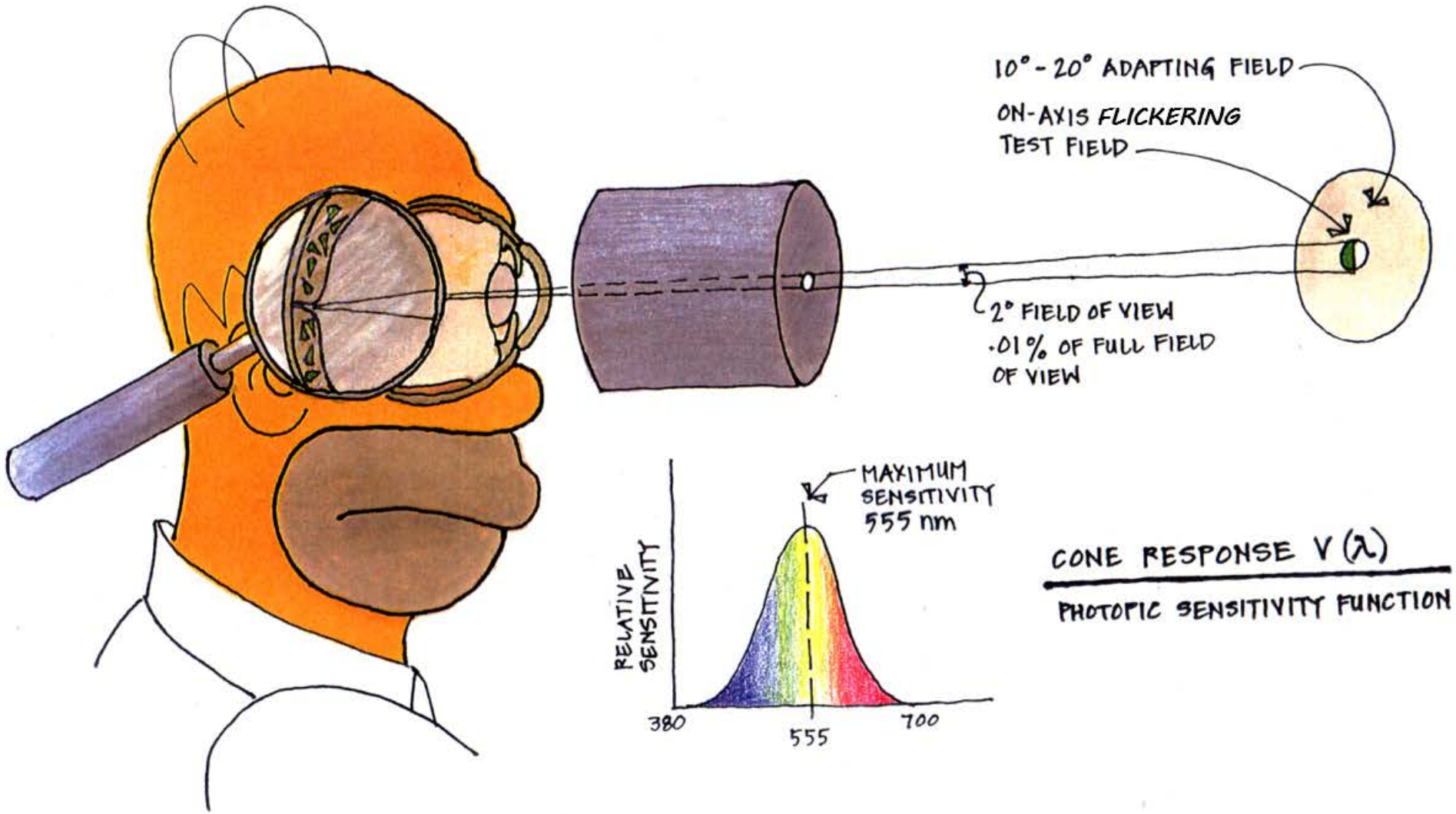

Sclera
Choroid
Retina
Cornea
Pupil
Lens
Iris
Ciliary body
Optic nerve
Fovea
LIGHT

Conditions of CIE Photometry – 75 years ago

The Photopic (Cone) Sensitivity Function, V (λ), is basic to Vision Science.

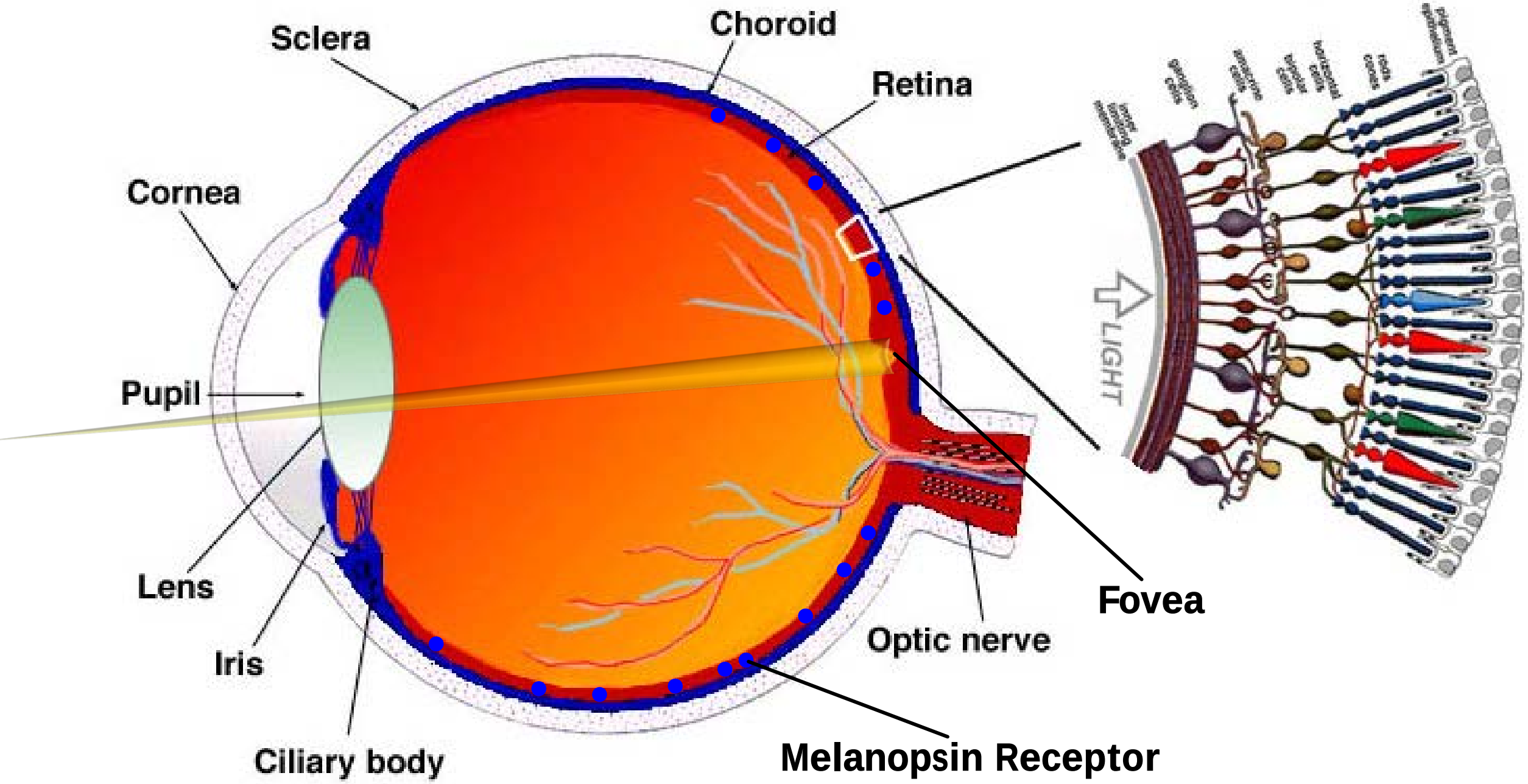
Determined by restricting the visual conditions to isolate the Cones.

Foveal (Tunnel) Vision

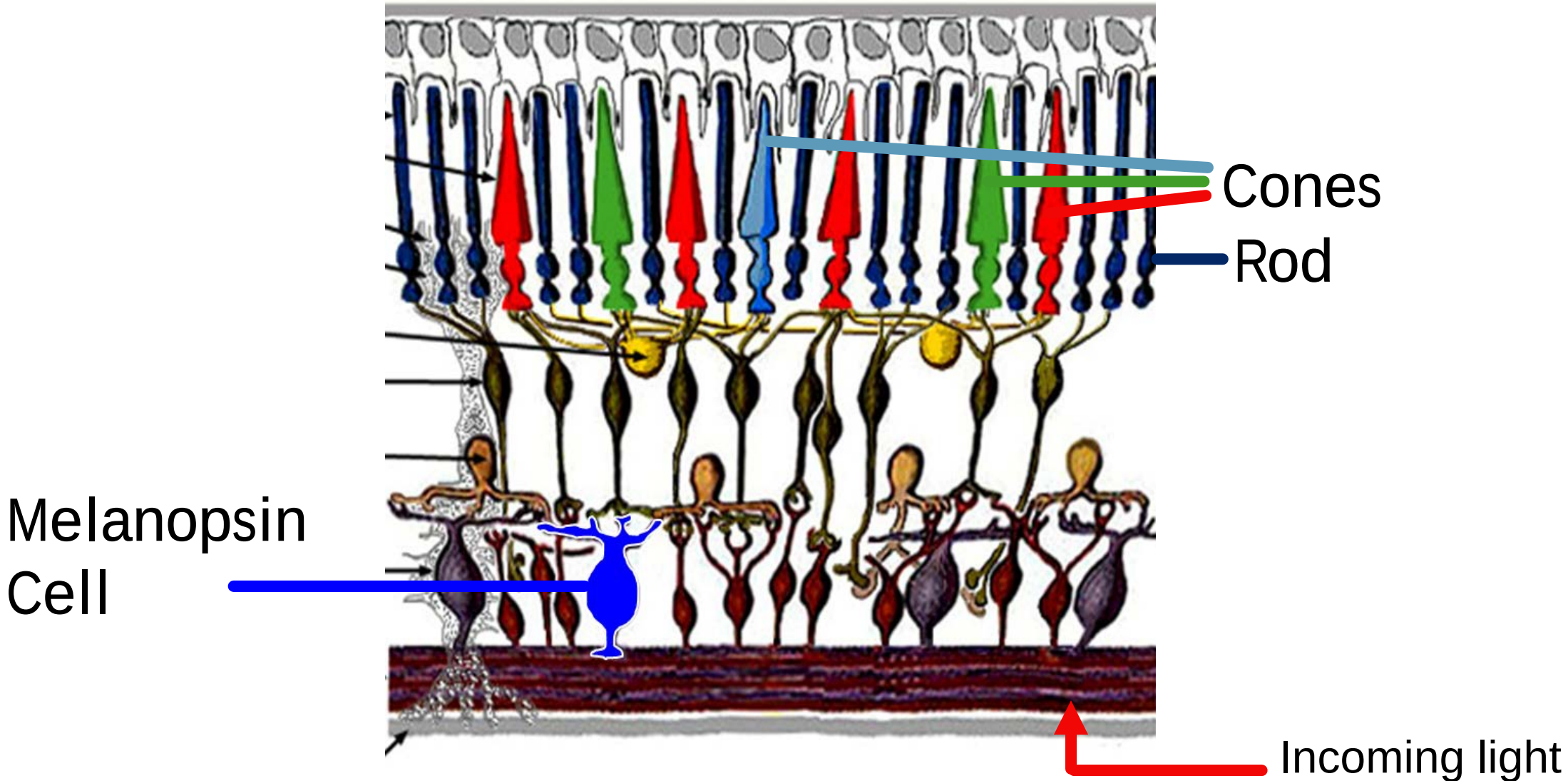


What have we here?!!!

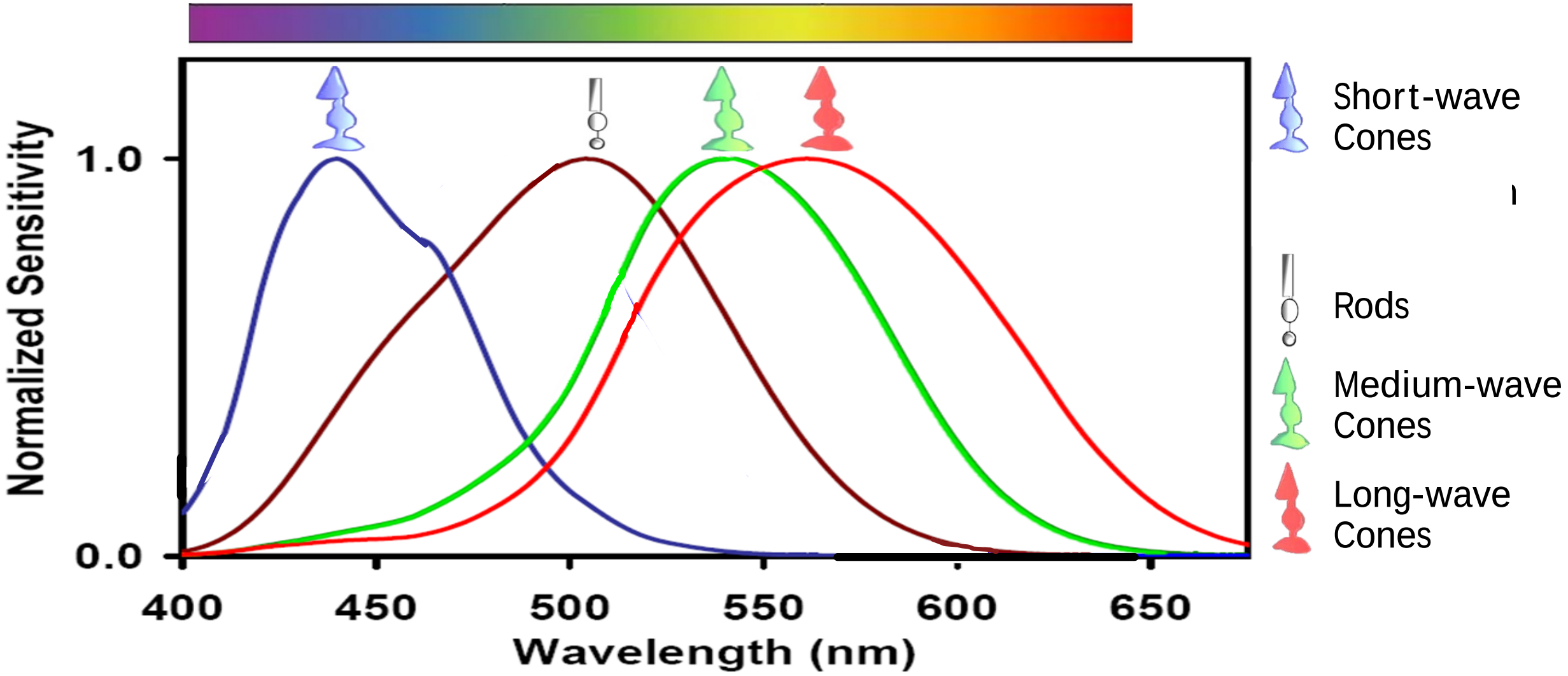
Oh my! A new retinal receptor functioning primarily at photopic levels with a peak sensitivity around 490 nm – very close to the rod peak sensitivity of 508 nm!


Sclera
Choroid
Retina
Cornea
Pupil
Lens
Iris
Ciliary body
Optic nerve
Fovea
Melanopsin Receptor
LIGHT

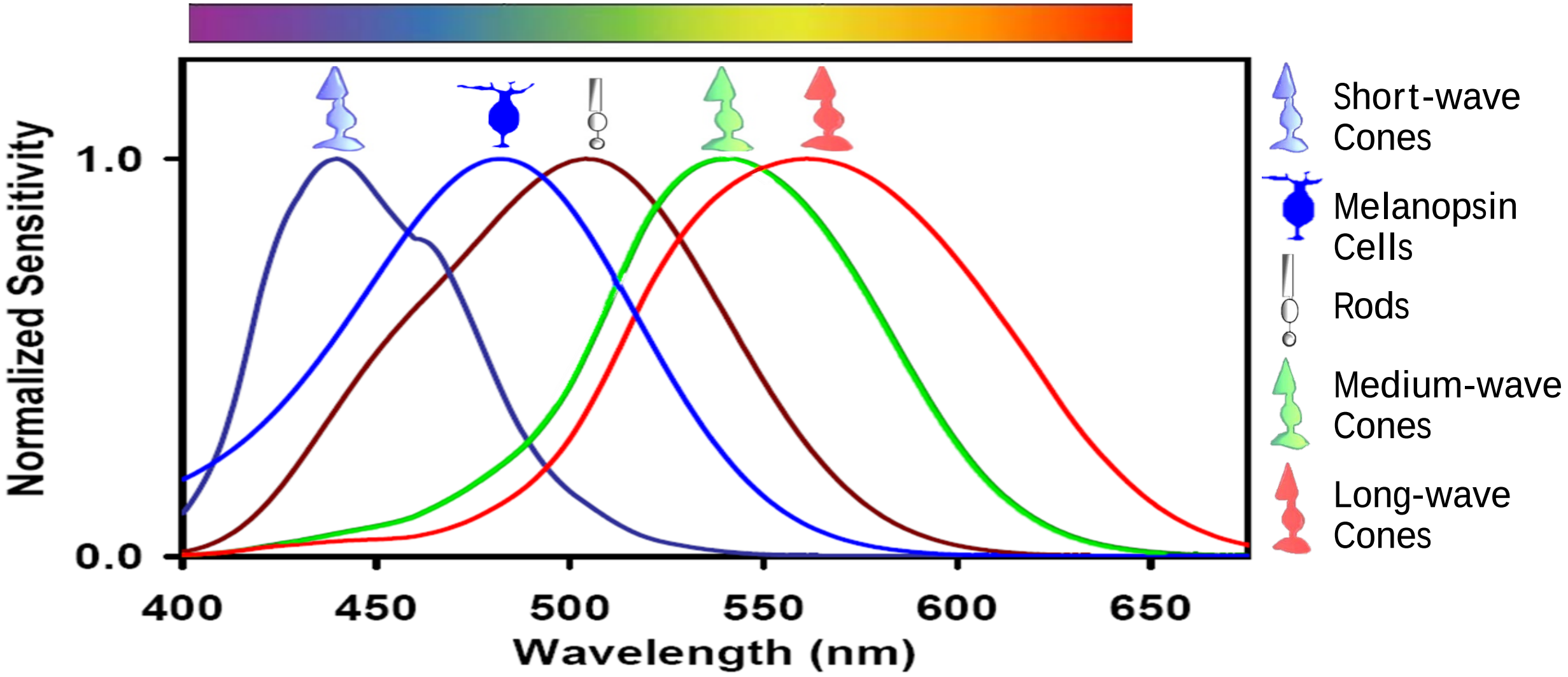
Retinal Anatomy Showing Cones, Rods and Melanopsin Receptors



Spectral Sensitivity of All Known Photoreceptive Cells Before 2000



Spectral Sensitivity of All Known Photoreceptive Cells After 2000

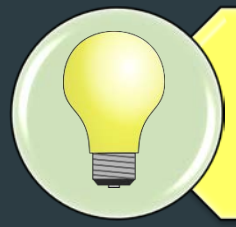


Quantifying the Melanopic Content

Use the ratio M/P (an intensity independent spectral descriptor)

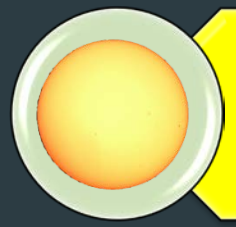
$$\text{M/P for a given spectrum} = \frac{\text{Spectrum weighted by the melanopic sensitivity function normalized to unity at its peak}}{\text{lumens associated with the same spectrum}}$$

Some Typical Values for M/P

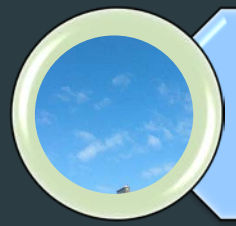


Incandescent lamp (100W): 0.65

Equal energy white: 1.2

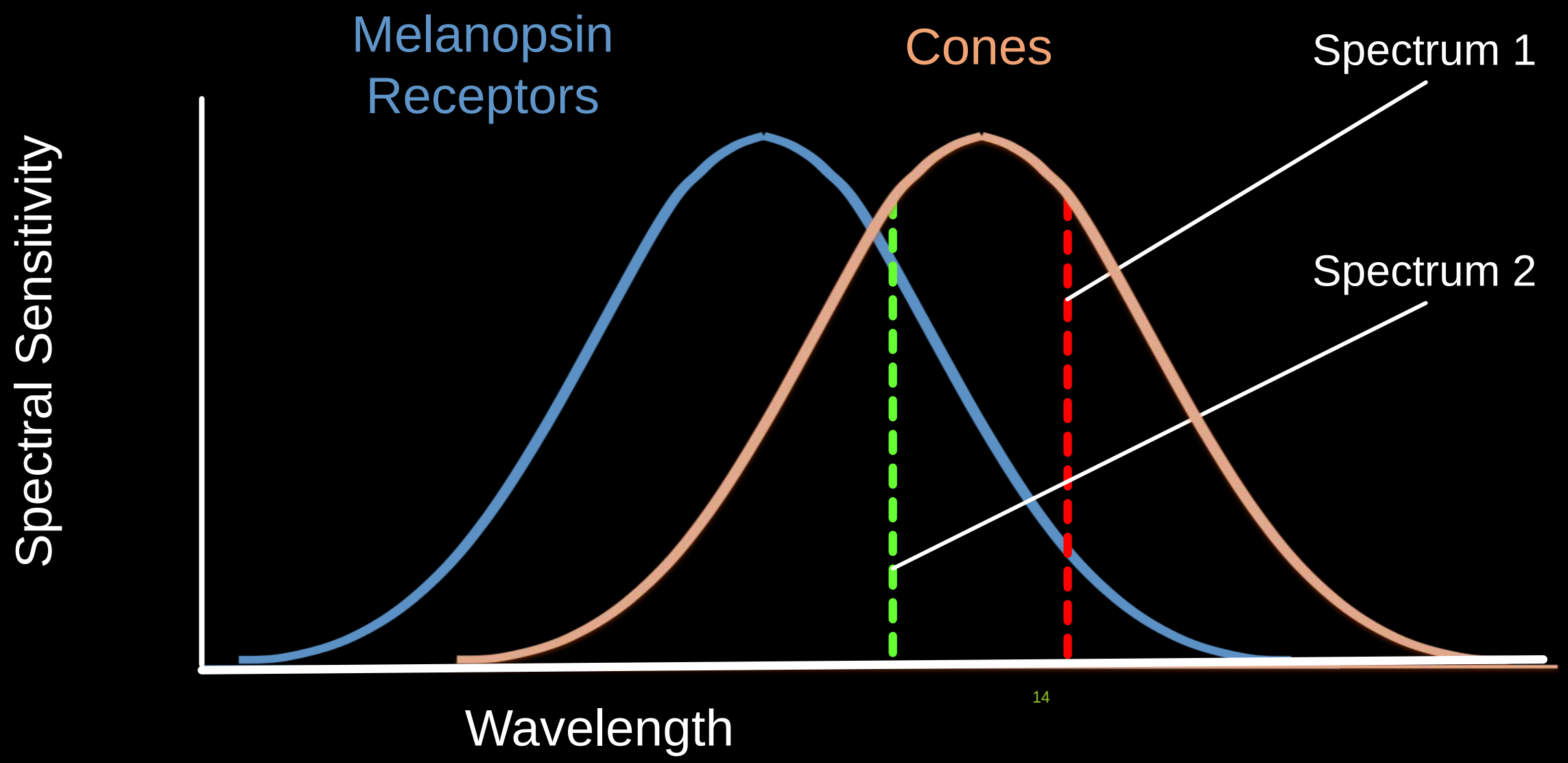


Sunlight (5000K): 1.07



Blue sky: 1.45

Metamerism Simplified



Purpose of this Study:

to confirm and to quantify melanopsin contributions as a component of brightness perception in a semi-realistic environment

Melanopsin & Brightness

Brightness perception (BP) is an essential feature of lighting practice

The quantitative contribution to brightness perception (BP) of melanopsin output is unknown

Establishing the features of melanopsin reception applicable to lighting practice couples vision science and illuminating engineering

What is Needed

Previous studies* based on brightness comparison are indicative of melanopsin spectral effects

*Berman et al 1990; Brown et al 2012; Royer & Houser 2012

The conditions and/or the protocols employed such as small white rooms, unspecified test conditions, or possible color confounds, diminish confidence in these past studies

NEEDED:

1. Quantitative Information
2. Verification when only a portion of the visual field is lit

The Simulation

Our study employs a reasonable simulation of a typical athletic field of dimensions 70x45 m lit to nighttime playing conditions

Measured field illuminances in the direction of gaze (IDOG) for typical spectators and players are typically 60 Lux and 150 Lux respectively

These levels correspond to illuminations of 250-300 horizontal field Lux

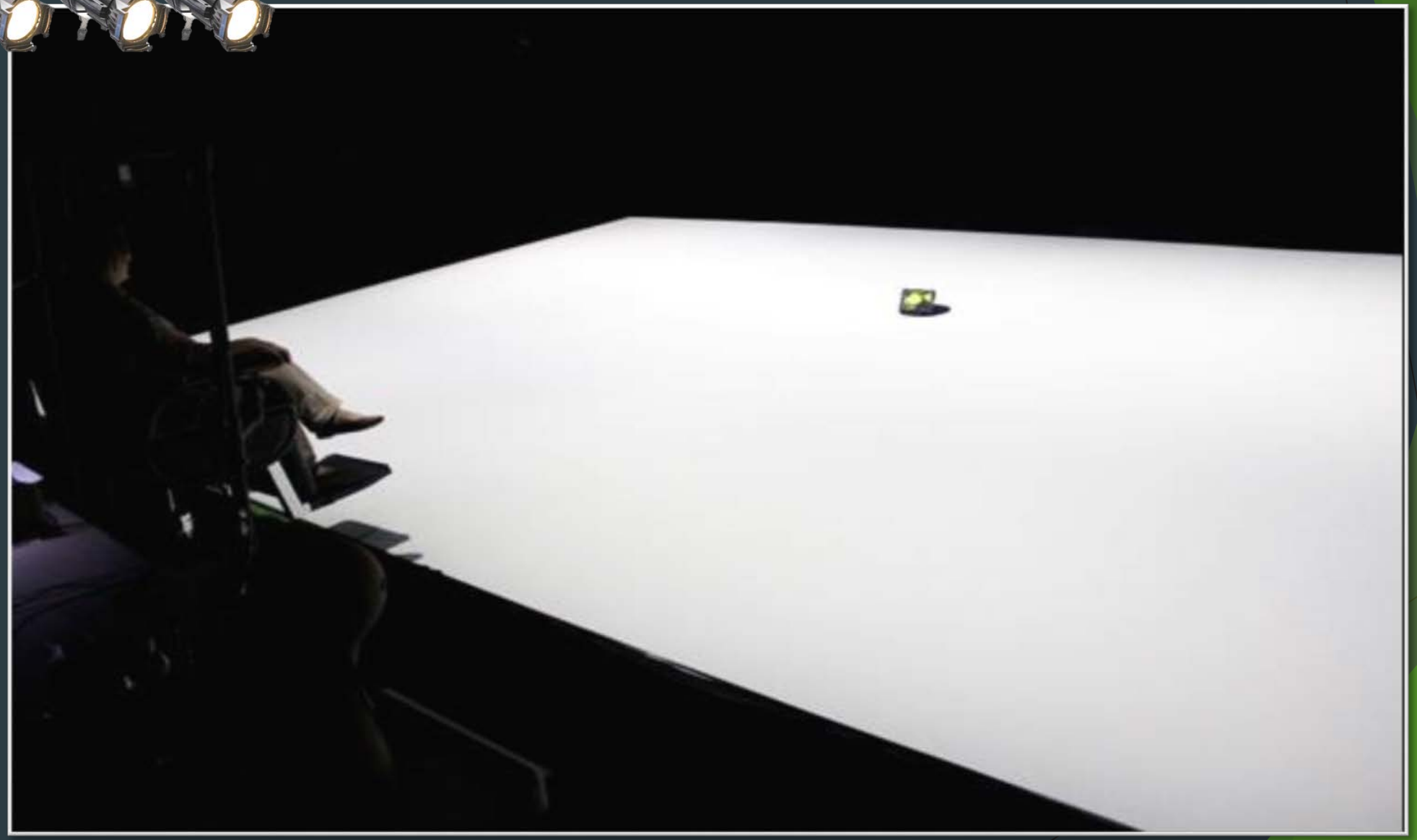
Those levels are the target values for the simulation

The Simulation

A simulation environment of size 6 x 9 m with test subjects seated at midpoint along one edge of the lit field was found sufficient to reproduce the same visual angles as in the real field (68^0 h, 56^0 v)

Lighting such a space with a variety of metamers along with providing the target IDOGs proved to be a difficult but eventually doable challenge

The Simulation



iPad Mini

Black Circle to Defeat Maxwell Spots

Theatrical Fixture

Eliminating Confounds

Isolating the melanopsin effect to BP from color channel contributions requires that the test lighting be truly metameric

Color differences can confound brightness judgments especially for naïve subjects

Test Design

Test design is a threefold task to provide

1. A range of metamers of different melanopsin content
2. Uniform lighting on the test field
3. The measured illuminances both DOG and horizontal

Creating the Metamers

Methodology of Cohen & Kappauf

1982, 1985

Based on the Wyszecki 'black metamer' concept

1956, 1958

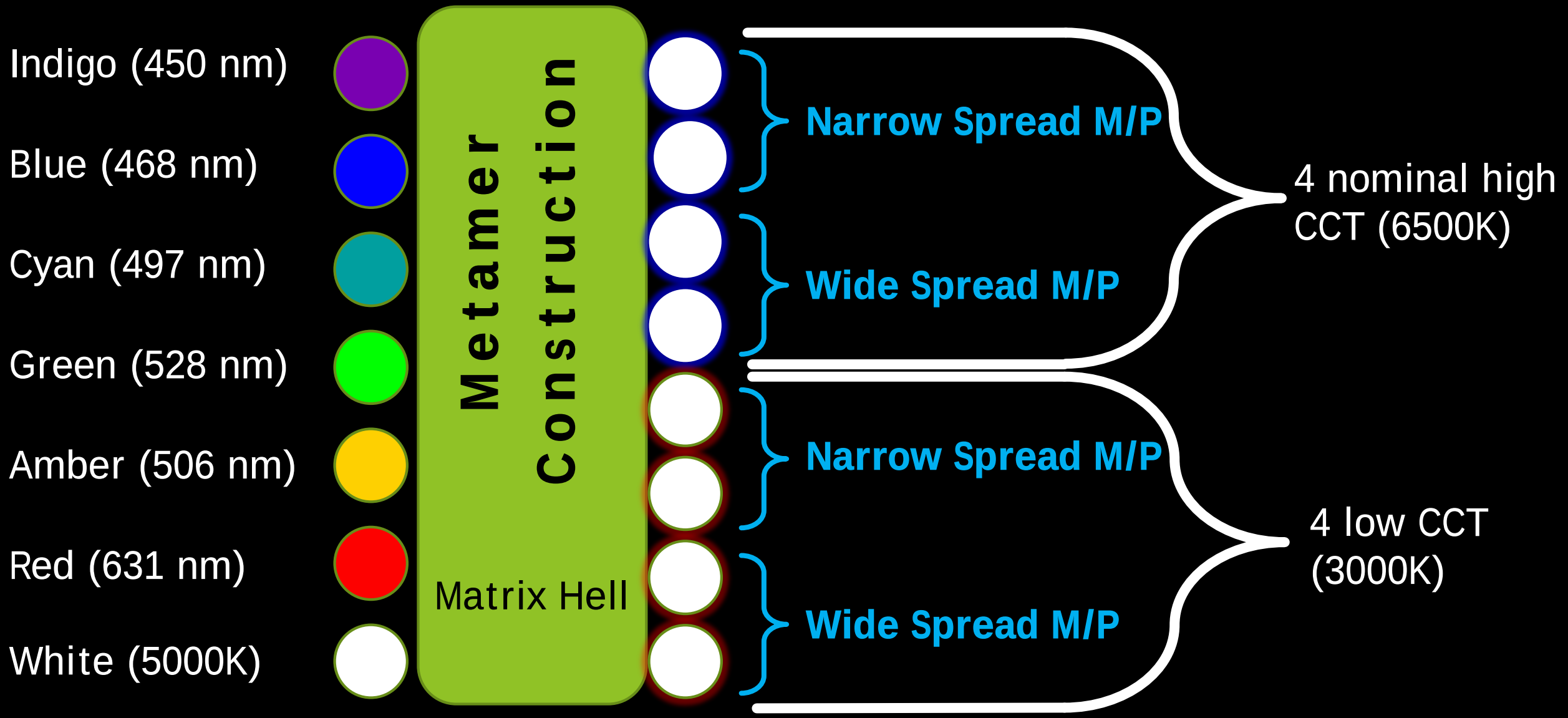
Exploited by Vienot et al

2012

Need 7 different color LED light sources

Need

The 7 LED Types



Lighting Construction

15 fixtures are required (ETC Source 4) containing 60 Luxeon Rebel Emitters, each with the 7 different color LEDs

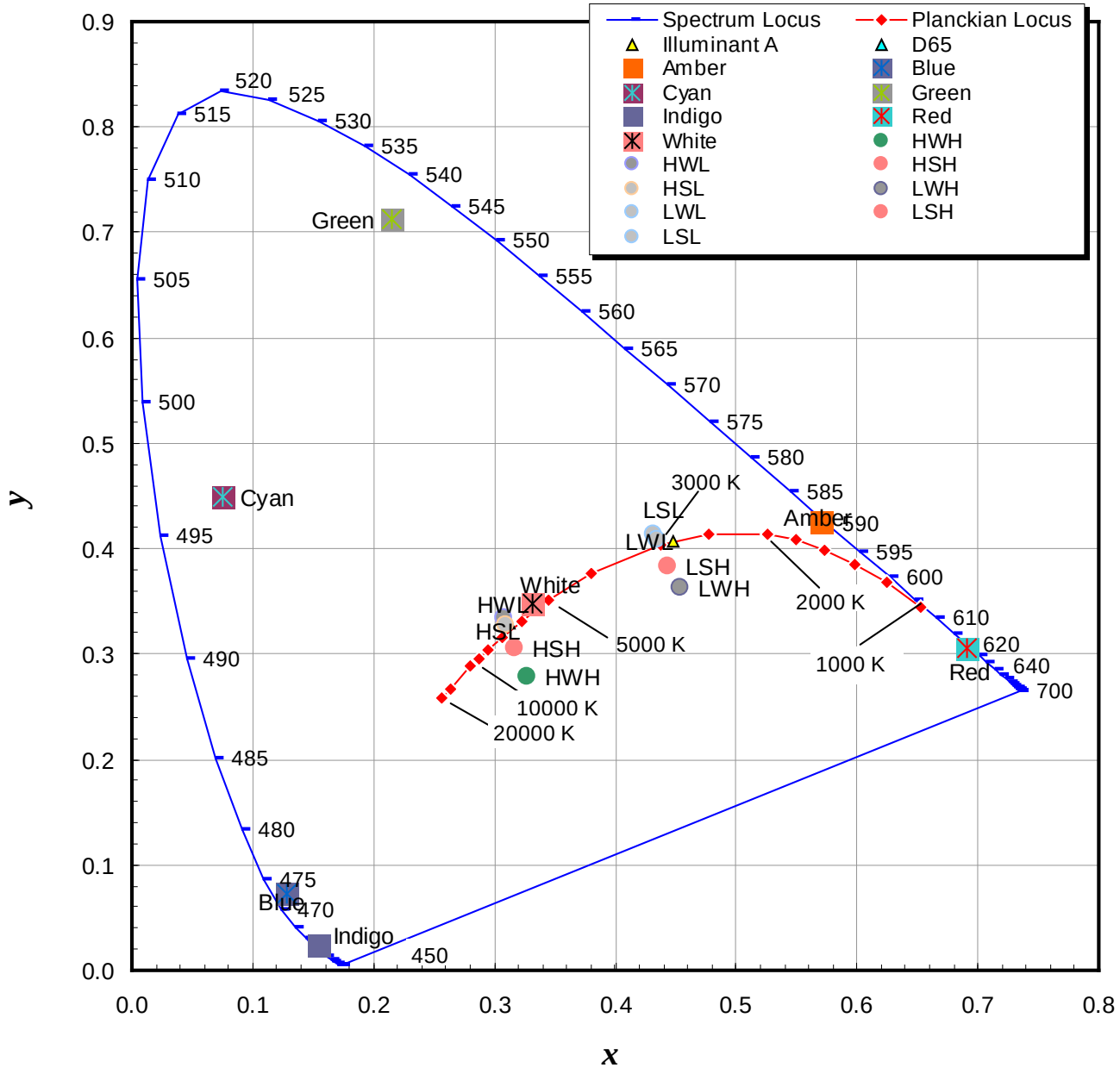
Metamer construction employs Stockman-Sharpe cone fundamentals (www.cvrl.org)

CIE (2006) “Fundamental chromaticity diagram with physiological axes – Part 1 Technical Report 170-1”

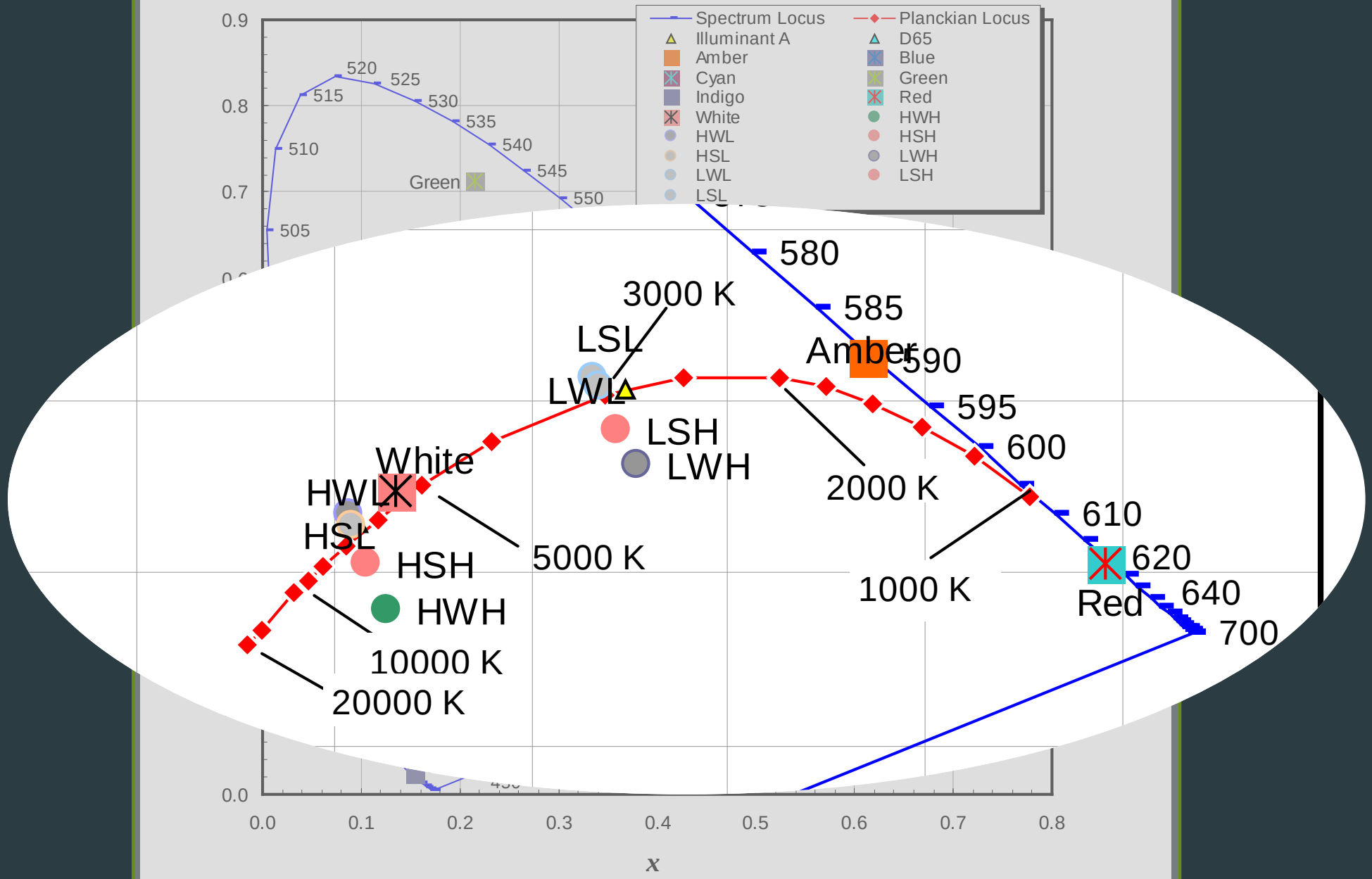
Lighting Conditions

			DOG Illuminance Levels			DOG Illuminance Levels		
			60 Lux	150 Lux	400 Lux	60 Lux	150 Lux	400 Lux
Pair	Description	Code	M/P	M/P	M/P	CCT	CCT	CCT
1	High CCT	HWH	2.389	2.381		5653K	5475K	
	Wide M/P Spread	HWL	1.019	1.011		6580K	6380K	
		Delta	1.370	1.370		-927	-905	
2	High CCT	HSH	1.769	1.746	1.744	6444K	6224K	5992K
	Small M/P Spread	HSL	1.064	1.056	1.056	6706K	6588K	6434K
		Delta	0.705	0.690	0.688	-262	-364	-442
3	Low CCT	LWH	1.443	1.430		2389K	2373K	
	Wide M/P Spread	LWL	0.511	0.519		3103K	3149K	
		Delta	0.932	0.911		-714	-776	
4	Low CCT	LSH	1.106	1.093		2713	2688	
	Small M/P Spread	LSL	0.592	0.597		3040K	3054K	
		Delta	0.514	0.496		-327	-366	

CIE 1931 x,y Chromaticity Diagram



CIE 1931 x,y Chromaticity Diagram



CIE Chromaticities

			x	y
ETC Fixture LEDs		Amber	0.57008832	0.4254393
		Blue	0.12834257	0.07196647
		Cyan	0.07471827	0.44943634
		Green	0.21526944	0.71237339
		Indigo	0.15496653	0.02445878
		Red	0.69144718	0.3060068
		White	0.33216667	0.34852191
Metamers	Pair 1	HWH	0.32770185	0.27789021
		HWL	0.30860619	0.33417159
	Pair 2	HSH	0.31676138	0.3053155
		HSL	0.3097961	0.32782542
	Pair 3	LWH	0.45348965	0.36226765
		LWL	0.43222807	0.41451669
	Pair 4	LSH	0.44308589	0.38390005
		LSL	0.43485578	0.4085055

Subjects

Musco employees with no knowledge of lighting

Not medicated with known pupil reaction modifiers

47 subjects in 3 age groups qualified

The Overall Study was Divided into 3 Sub-Studies

Brightness Comparison (BC), metamers at equal IDOG

Pupil Sizes during the BC evaluation (PS)

Brightness Matching where IDOG is adjusted to perceived equality (BM)


Summary of Subject
Participations for all
3 Studies by Age Group

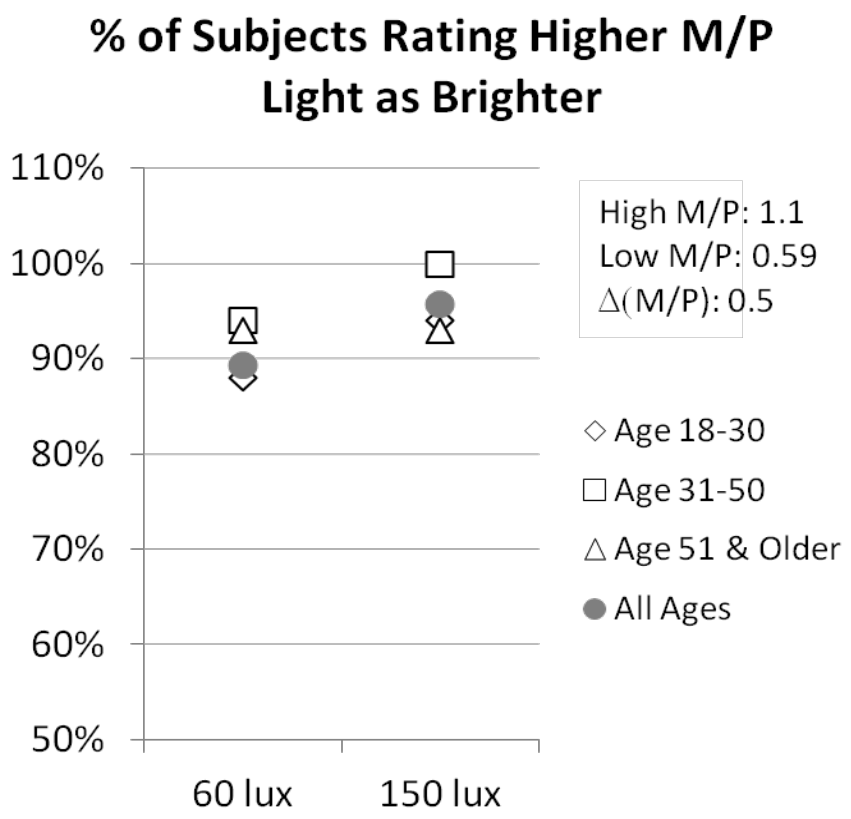
Subjects by Age Group for All Sub-studies

Subject Age Group	Brightness Contrast Test	Pupil Size Test	Brightness Matching Test
Age 18-30	17	14	16
Age 31-50	16	13	12
Age 51 & over	14	13	12
TOTAL No. of Subjects	47	40	40

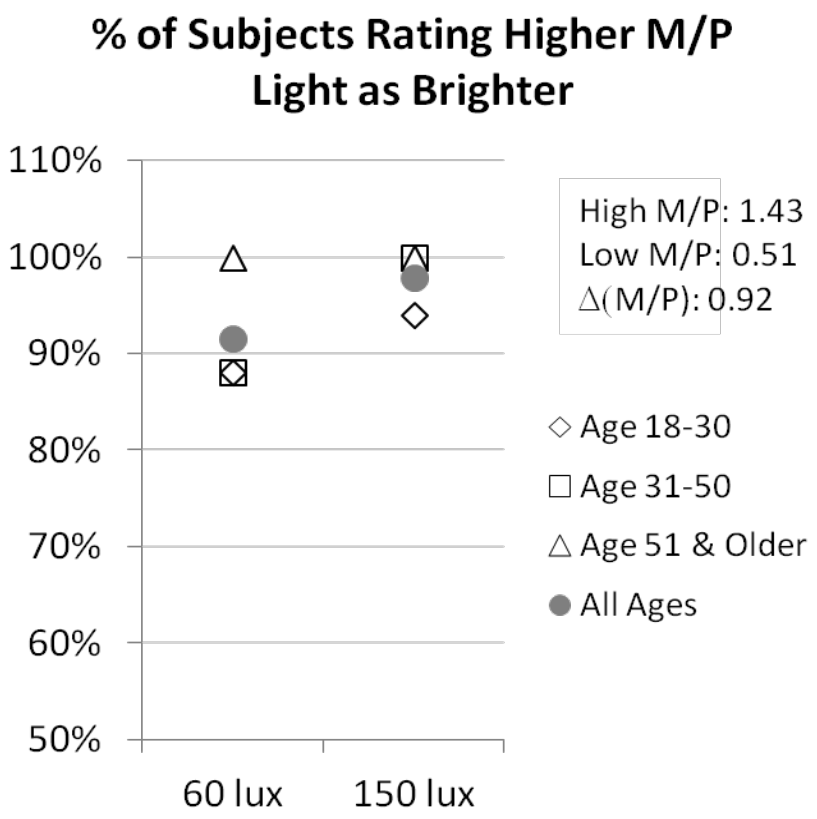
Brightness Contrast Subject Protocol

- 2 min adaptation to first condition focusing on IPad Mini
- The 2 compared scenes transition time 1 sec, observation/decision time 5 sec
- Metamerism maintained during transition of 5 intervals of 200 msec each
- 3 repetitions referred to as “A” or “B”
- Subjects asked “Which is brighter?”
- Experimenter not informed, and order randomized

Low Correlated Color Temperature Illuminants with Small and Wide Spread ΔM/P Ratios



Low CCT, Small Spread (ΔM/P = 0.5)



Wide Spread (ΔM/P = 0.92)

Brightness Comparison Results for 47 Subjects

% of Subjects higher M/P lighting as brighter

		High M/P	*1.769*	*1.746*	*1.744*	*1.106*	*1.093*	*2.389*	*2.381*	*1.443*	*2.582*
		Low M/P	*1.064*	*1.056*	*1.056*	*0.592*	*0.597*	*1.019*	*1.011*	*0.511*	*0.519*
		Delta M/P	*0.705*	*0.690*	*0.688*	*0.514*	*0.496*	*1.370*	*1.370*	*0.932*	*0.911*
BC Test by age group		Avg Across Tests	**HS-60**	**HS-150**	**HS-450**	**LS-60**	**LS-150**	**HW-60**	**HW-150**	**LW-60**	**LW-150**
18--30	17	83%	65%	76%	82%	82%	94%	76%	88%	88%	94%
31--50	16	91%	81%	81%	88%	94%	100%	94%	94%	88%	100%
51--Older	14	92%	86%	93%	93%	93%	93%	79%	93%	100%	100%
Total	***47***	***88%***	***76.6%***	***83.0%***	***87.2%***	***89.4%***	***95.7%***	***83.0%***	***91.5%***	***91.5%***	***97.9%***
Ave for both light levels			***79.8%***			***92.6%***		***87.2%***		***94.7%***	

Results

- Higher M/P sources were perceived brighter 375 out of 423 chances
- The unbiased estimate of the probability is 88.5% ± 1.5%
- The probability of this result occurring by chance is 10^{-10}

Results

The analysis shows very high significance!

Thus the hypothesis that the M/P ratio affects brightness is confirmed in this sub-study

Results were significant for all age groups

Pupil Size Measurements Results (nominal 150 Lux)

Test conditions and average pupil sizes

Test	Lux	SE	M/P	SE	Diameter	SE
1a	150.55	0.11	1.06	0.0007	4.36 mm	0.14
1b	149.40	0.05	1.75	0.0044	4.12 mm	0.14
2a	149.66	0.06	1.01	0.0005	4.48 mm	0.13
2b	149.15	0.13	2.38	0.0042	3.75 mm	0.12

Comment

For the wide spread condition pupil area was 30% smaller under the high M/P lighting,
i.e. retinal illuminance effectively reduced by 30%

Nevertheless subjects chose the higher M/P condition as brighter

Is Pupil Size a Causal Factor in Brightness Perception?

Examine if there is a correlation between individual brightness choice and subject pupil size

Was pupil size always smaller when M/P was the larger?

Melanopsin & Brightness

Subject data shows no correlation when ratio of M/P values is the lower at 1.65 and weak correlation when the ratio of M/P values is the higher at 2.36

Pupil size and brightness are likely to be both correlated to a causal factor and that pupil size is not the independent causal factor in brightness perception

Brightness Matching and Limen Testing Protocol

- Subjects provided with a manual slider for controlling light level
- Subjects given multiple chances to move slider to adjust light intensity of scene A randomly chosen as either high M/P or low M/P so that scene B appears equally bright
- Initially Scene B is either 20% higher or lower than scene A
- Subjects told to judge equivalency in a short time period following switching (close to 1 second, no longer than 5 seconds)
- After achieving equivalent brightness, each scene presented for 5 seconds to confirm the equal brightness setting with the subject
- The subject was allowed final tweaking if subjects change their mind after viewing the conditions under the longer exposure

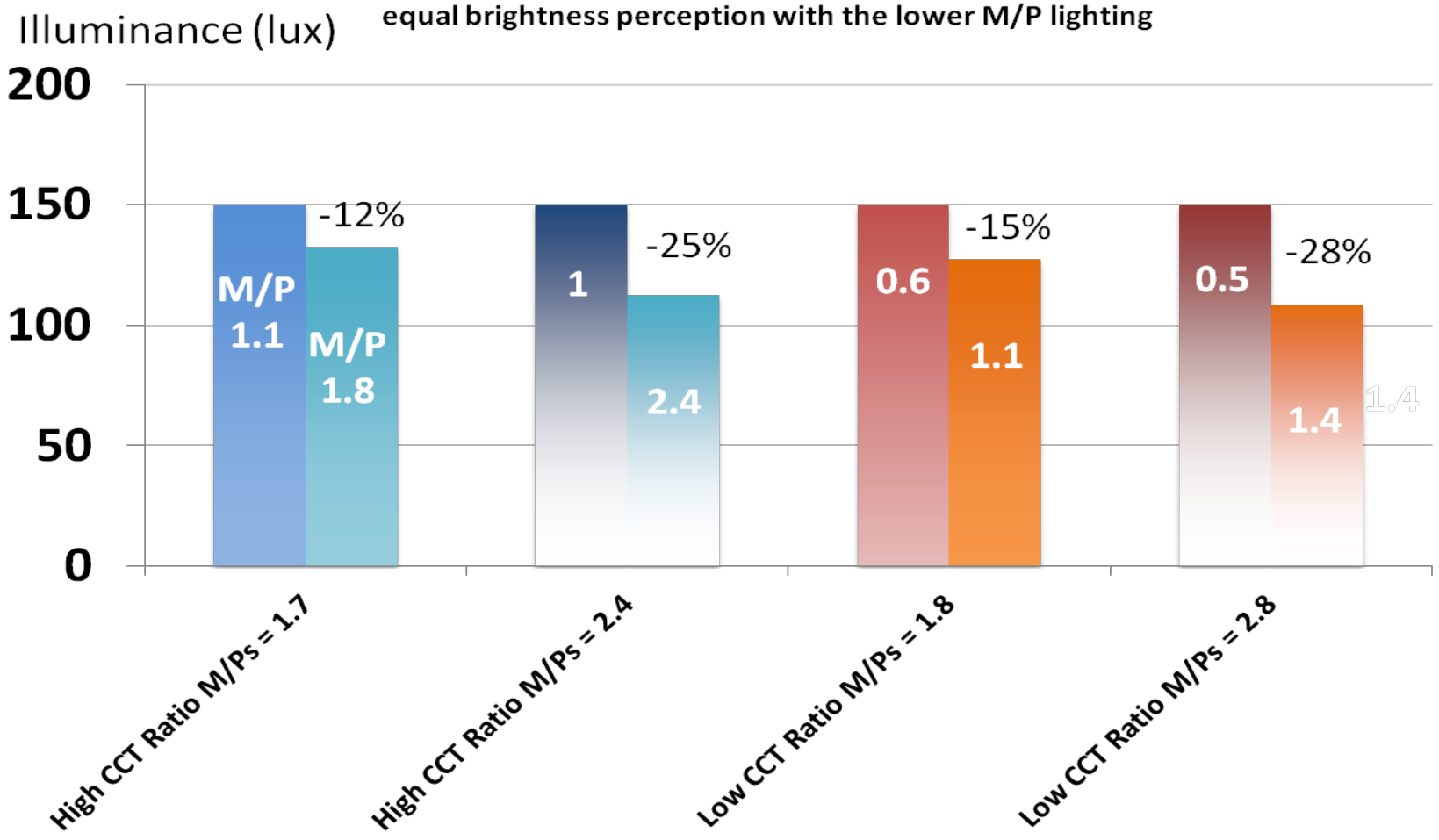
Results for the BM Tests

With 8 conditions for each subject, 32 of the 40 subjects chose a lower illuminance for the high M/P source compared to the low M/P source at a statistically significant level (7 out of 8 runs)

Overall, the high M/P source was set to a lower light level than the low M/P source 293 times out of 320 runs, which has a probability of 10^{-151} of happening if the true probability was 50%

Brightness Matching Results for 40 Subjects

Right columns show average lowered illuminance for the high M/P lighting to achieve equal brightness perception with the lower M/P lighting



``

			Brightness Matching Results for 40 Subjects: % of Subjects selecting lower Illuminance for high M/P lighting								
		HighM/P	1.769	1.746		1.106	1.093	2.389	2.381	1.443	1.430
		Low M/P	1.064	1.056		0.592	0.597	1.019	1.011	0.511	0.519
		Delta **M/P**	**0.715**	**0.690**		0.504	0.496	1.370	1.370	0.932	0.911
BM Test by age group		Avg Across Tests	**HS-60**	**HS--150**		**LS-60**	**LS-150**	**HW-60**	**HW-150**	**LW-60**	**LW-150**
18--30	16	87%	69%	63%		88%	88%	94%	94%	100%	100%
31--50	12	93%	83%	92%		100%	92%	83%	92%	100%	100%
51--Older	12	97%	100%	100%		83%	100%	100%	100%	92%	100%
Total	**40**	**92%**	**82.5%**	**82.5%**		**90.0%**	**92.5%**	**92.5%**	**95.0%**	**97.5%**	**100.0 %**
Ave for both light levels			**82.5%**			**91.3%**		**93.8%**		**98.8%**	

	Ave. Light Level Reduction (% Using Low M/P as base)								
Ave. Reduction Percentage (Using Low M/P as base)	**14.3%**	**11.7%**		**13.1%**	**15.1%**	**20.7%**	**25.1%**	**27.3%**	**27.9%**
Ave for both light levels	**13.0%**			**14.1%**		**22.9%**		**27.6%**	

Quantification

The principal purpose of the BM study was to determine quantitatively the amount of light level reduction required for the higher M/P lighting to produce the perception of brightness equality

A simple quantitative model for including Melanopsin effects argues to replace P in the Stevens law of brightness by the quantity $[P(M/P)^n]$

Thus brightness B has the form:

$$\log B = \text{const} \times \log [P(M/P)^n]$$

Quantification

If perceived brightness is equal at 2 different known photopic levels P_1 & P_2 then because of 2 different known M/P values associated with the viewed spectra the exponent n can be determined from the data

Each subject's data is fit by the expression:

$$\log(P_1/P_2) = n \log[(M/P)_2/(M/P)_1]$$

The exponent n determined for the entire subject sample has the average value and s.e. of n = 0.318 ± 0.019

There was no significant difference by age.

Equivalent Brightness

When comparing brightness across different spectra, the quantity $[P(M/P)^{0.318}]$ replaces the photopic measure P and serves as the spectrally corrected measure of equivalent brightness perception

Note that the exponent is independent of the choice of normalization of M because it depends on the ratios of M/P

The Question of CCT

Is there an effect of CCT?

Examine interaction between M/P and CCT by testing for difference in the exponent between low and high CCT

A within subject comparison matching the illuminances, and the M/P ratios gave 160 differences between the high and low CCT runs

The Question of CCT

The difference of slider settings for high - low CCT was 0.013 ± 0.034, which is not statistically significant

Reject hypothesis of an interaction

Conclude that there is no effect of CCT on brightness matching separate from the M/P effect

Discussion

Rod receptors unlikely because of the similarity of results for 60, 150 and 400 Lux

Is the protocol of rapid alternation between metamers accounting for the full effect of melanopsin activation?

Is a steady state study possible?

Conclusions

For large fields of view, melanopsin output affects brightness perception independent of color

Photopic illuminance compensation is determined

Because of this compensation, light meters are veridical only if spectrum is constant

"Equivalent Brightness": $B=[P(M/P)^{0.32}]$

Based on maintaining brightness perception there is the potential for large (25%) lighting energy savings

Based on maintaining brightness perception there is the potential for large (25%) lighting energy savings


High M/P
Low M/P


High M/P
Low M/P

Thank you!