Lecture 8: Visual Adaptation and Constancy

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Computer Imaging & Graphics

The Roadmap

Theoretical Preliminaries

Human Visual Systems

Display and Camera

Modeling and Rendering

Overview

Color Vision

Colorimetry

Visual Adaptation

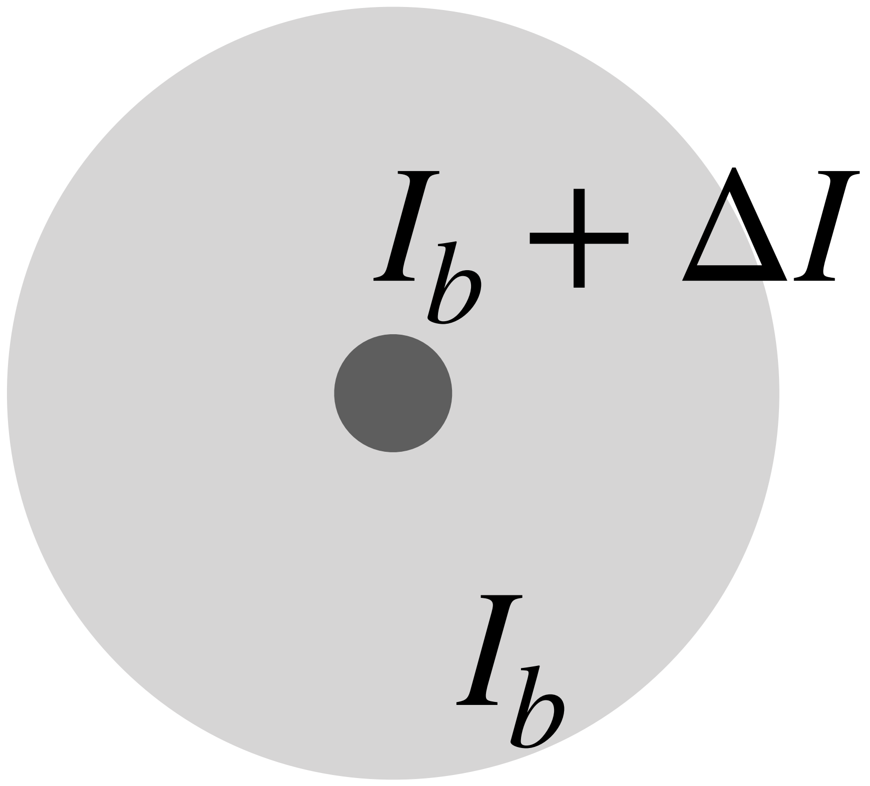
Light Adaptation

Behavioral Phenomena

- Desensitization at higher background light levels
  - Behavior ← RGC ← Photoreceptor
  - Behaviorally: threshold vs. (background) intensity curve
  - Neurally (RGC and photoreceptor): response vs. (flash) intensity curve or sensitivity vs. (background) intensity curve
  - Can behavioral curve be derived from the neural curves, and can the two neural curves be derived from each other?
- Partial recovery of sensitivity after light exposure

Behavioral Desensitization

Threshold vs. Intensity (TVI)

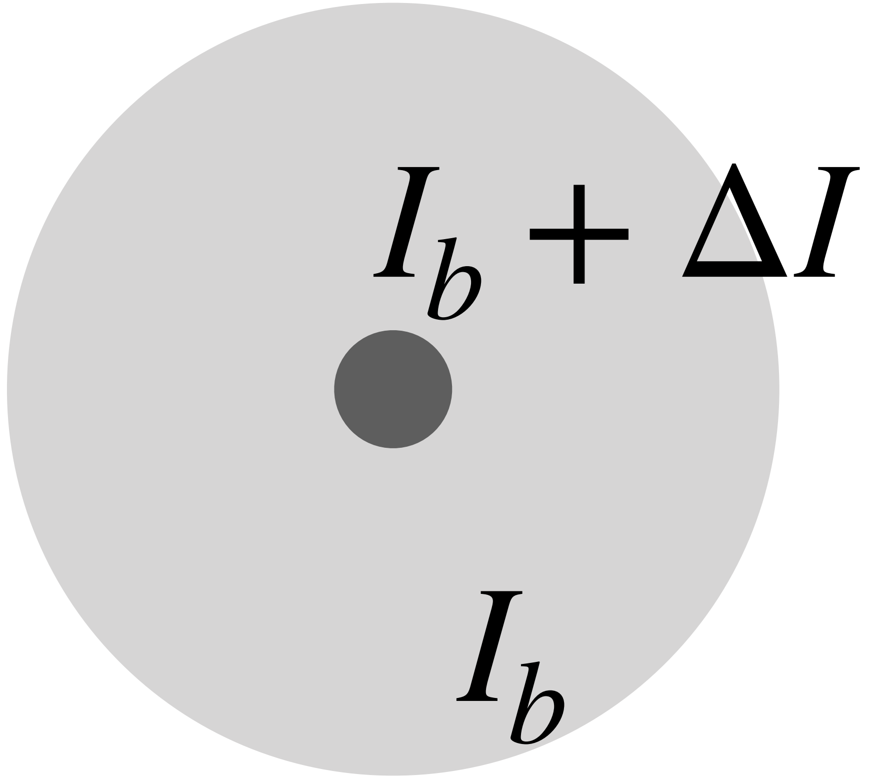


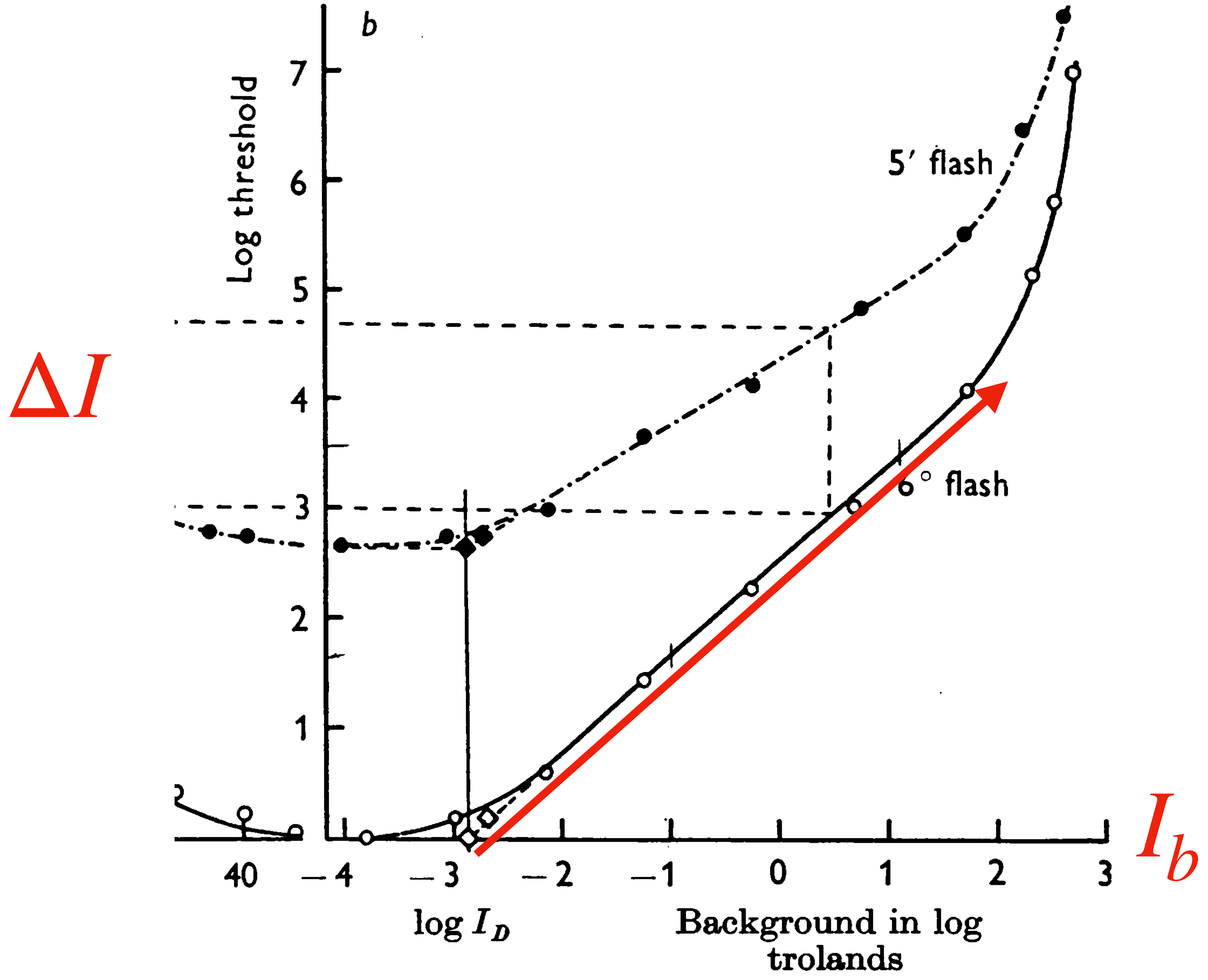
- Increment threshold experiment
  - Given a background light level (I_b), adjust the test light level ΔI ("increment") so that the test light is just barely noticeable.
  - ΔI is the Just Noticeable Difference (JND) under I_b.
  - Then repeat this for a wide range of background light levels.

https://webvision.med.utah.edu/imageswv/KallDark10.jpg

Behavioral Desensitization

$$\text{contrast} = \frac{\Delta I}{I_b} \approx \text{constant}$$





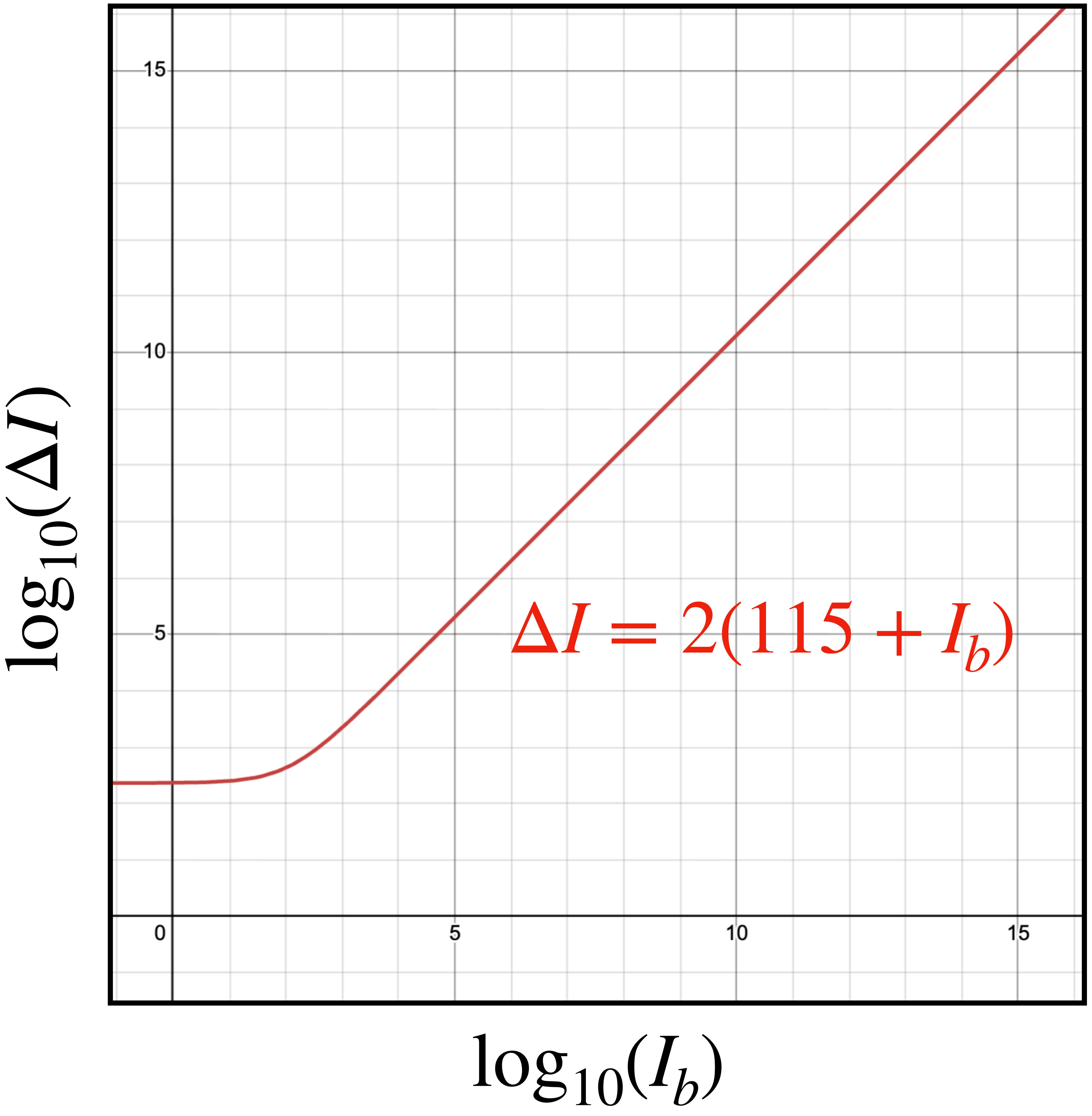
Weber-Fechner Law

Background intensity

"Dark light"

$$\Delta I = k(I_b + I_0)$$

Threshold for JND



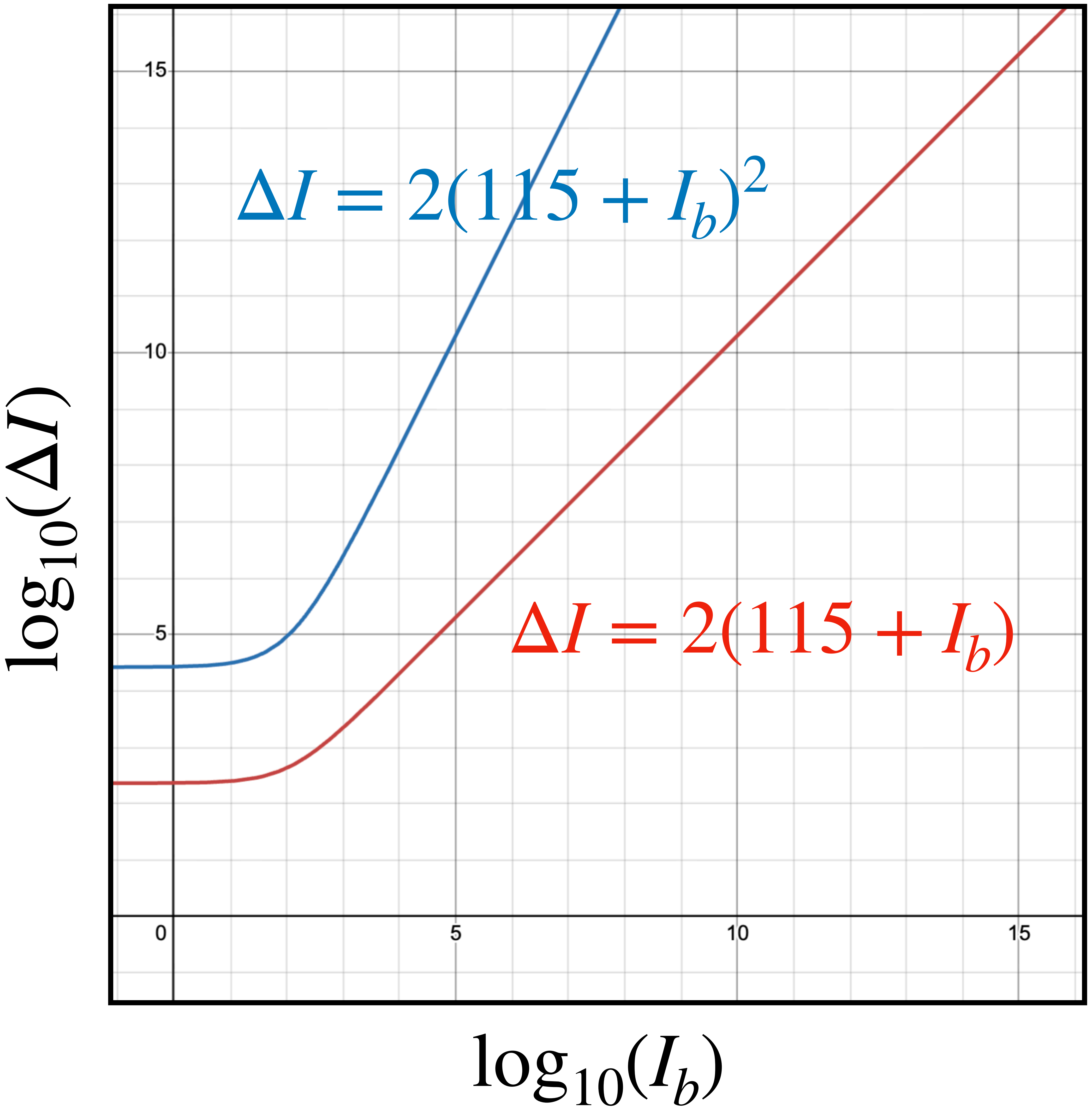
Generalized WF Law

Background intensity

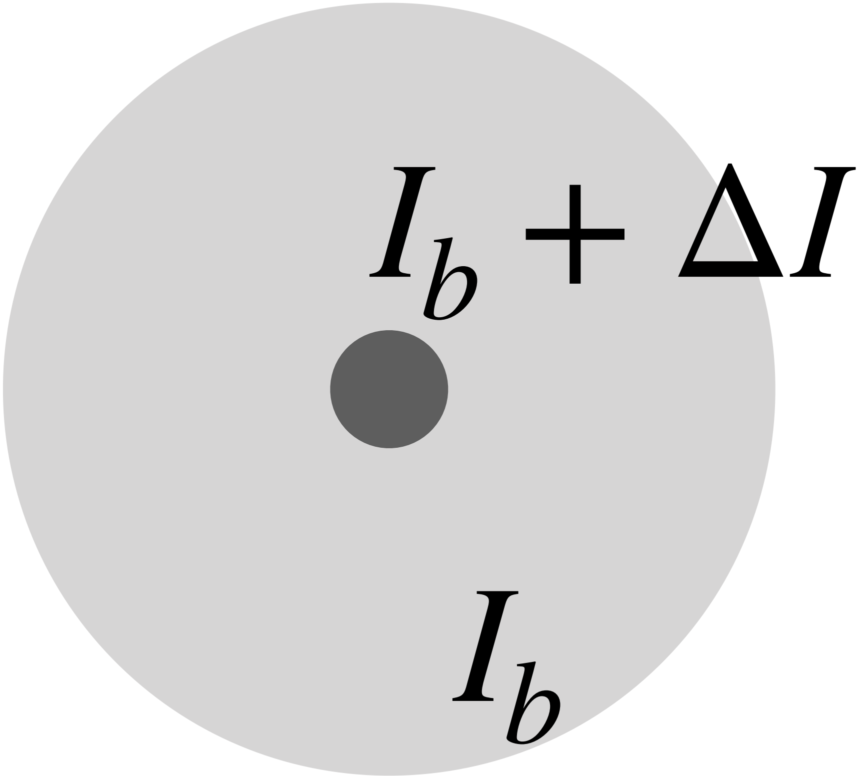
"Dark light"

$$\Delta I = k(I_b + I_0)^b$$

Threshold for JND

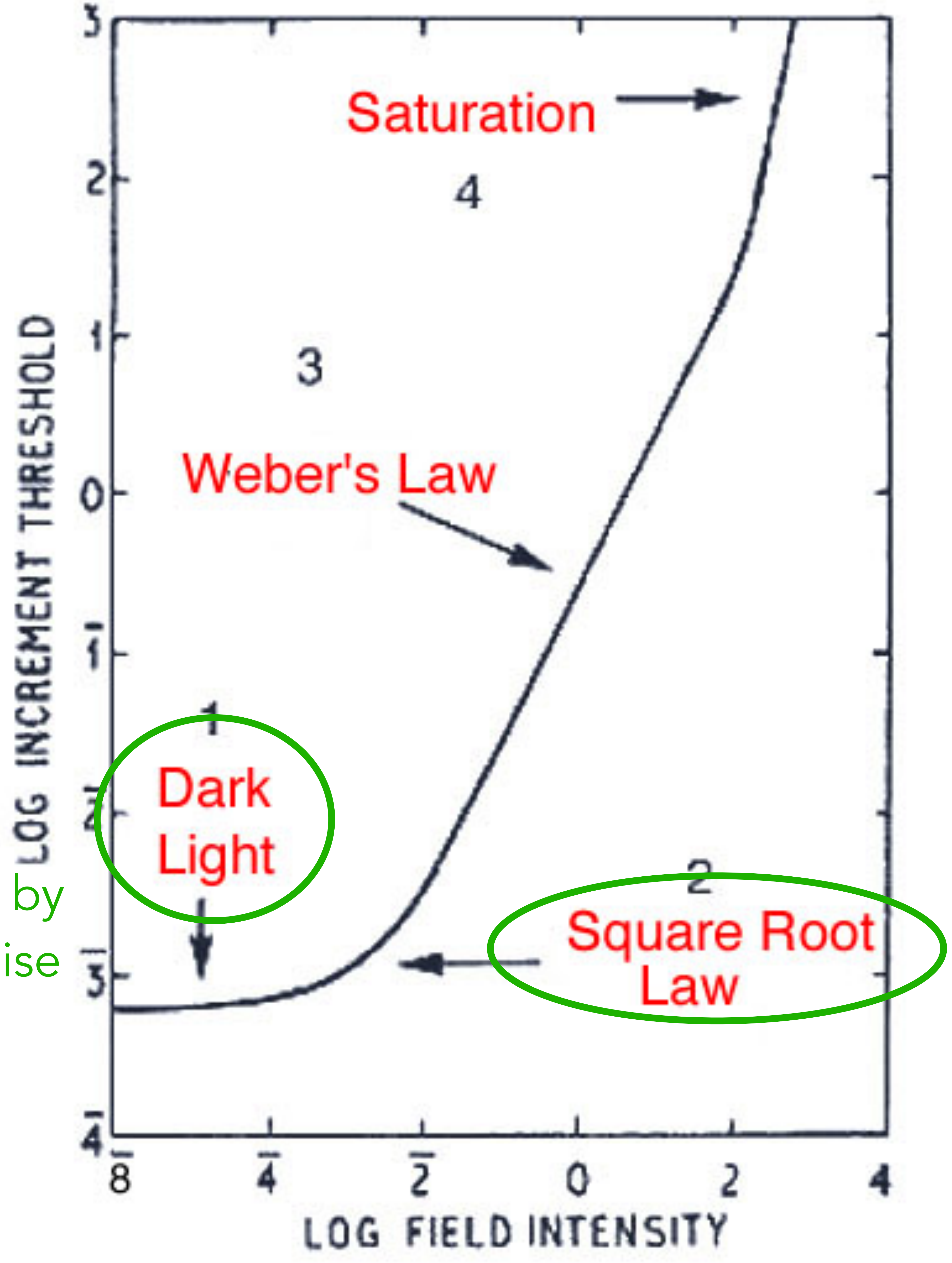


Four Regions



Sensitivity limited by internal neural noise

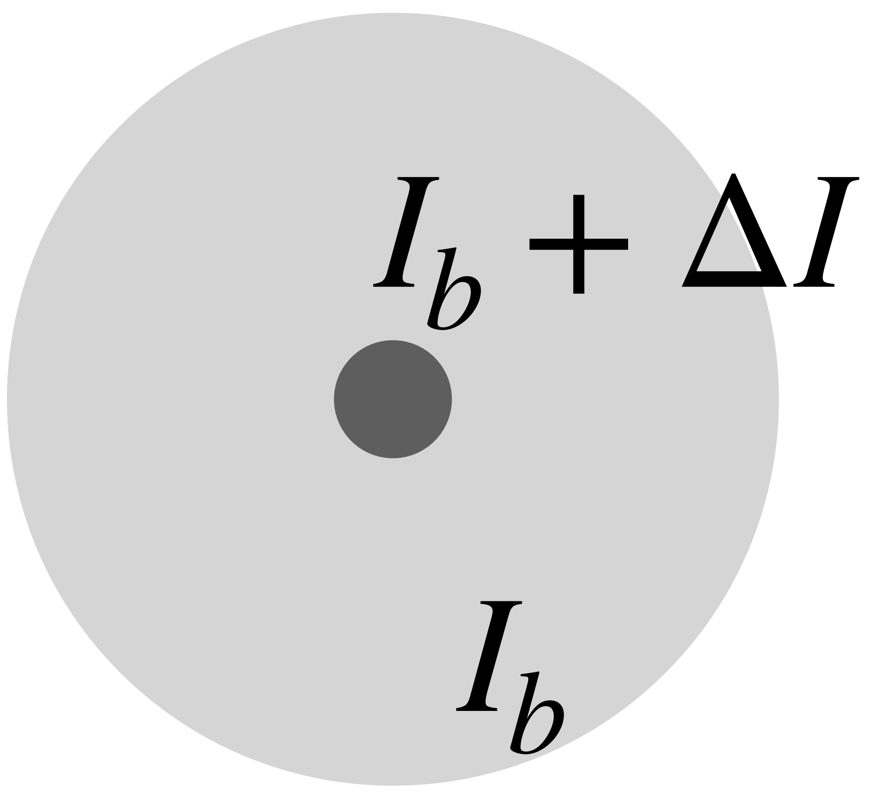
ΔI

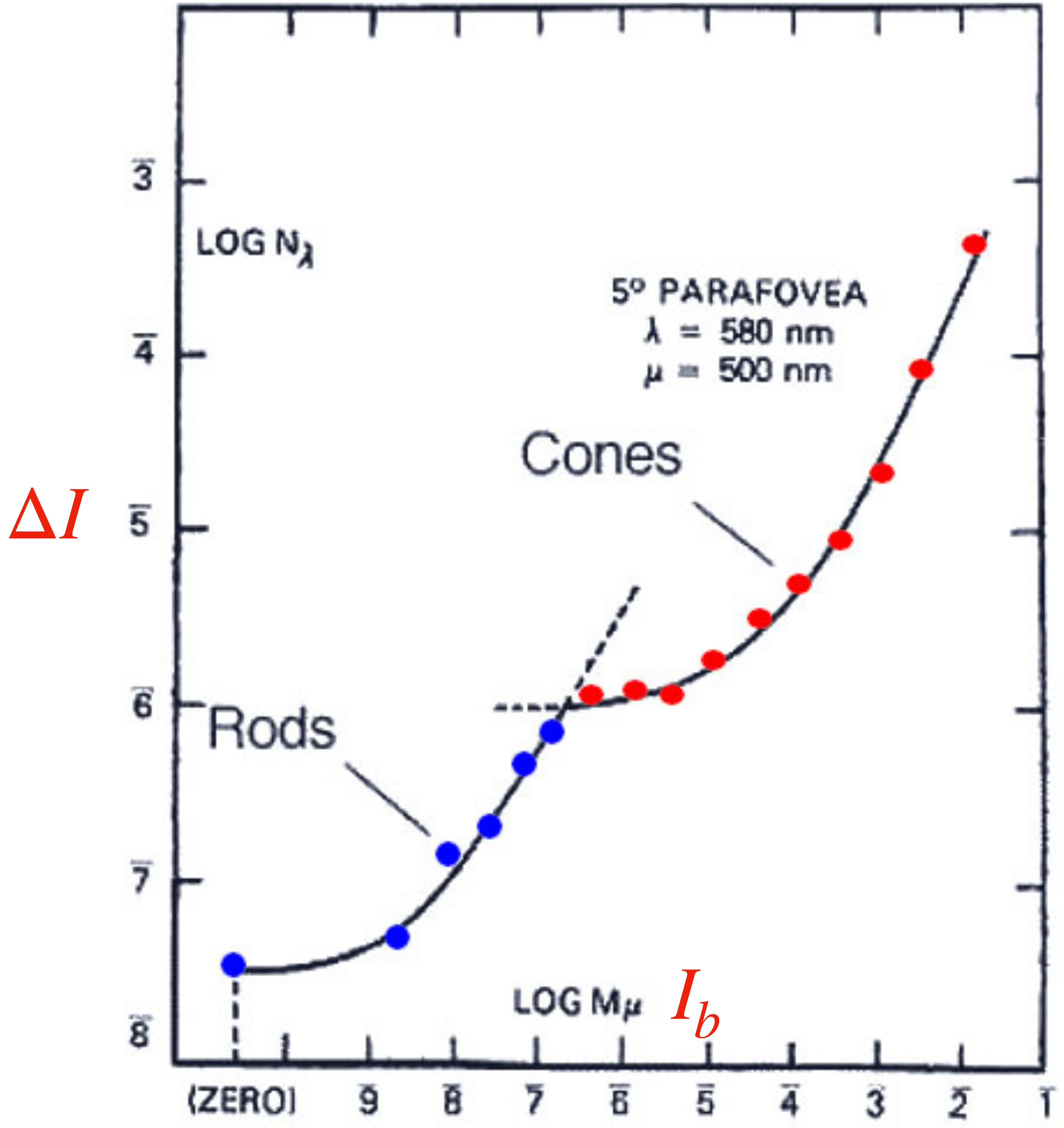


I_b

Sensitivity limited by photon shot noise

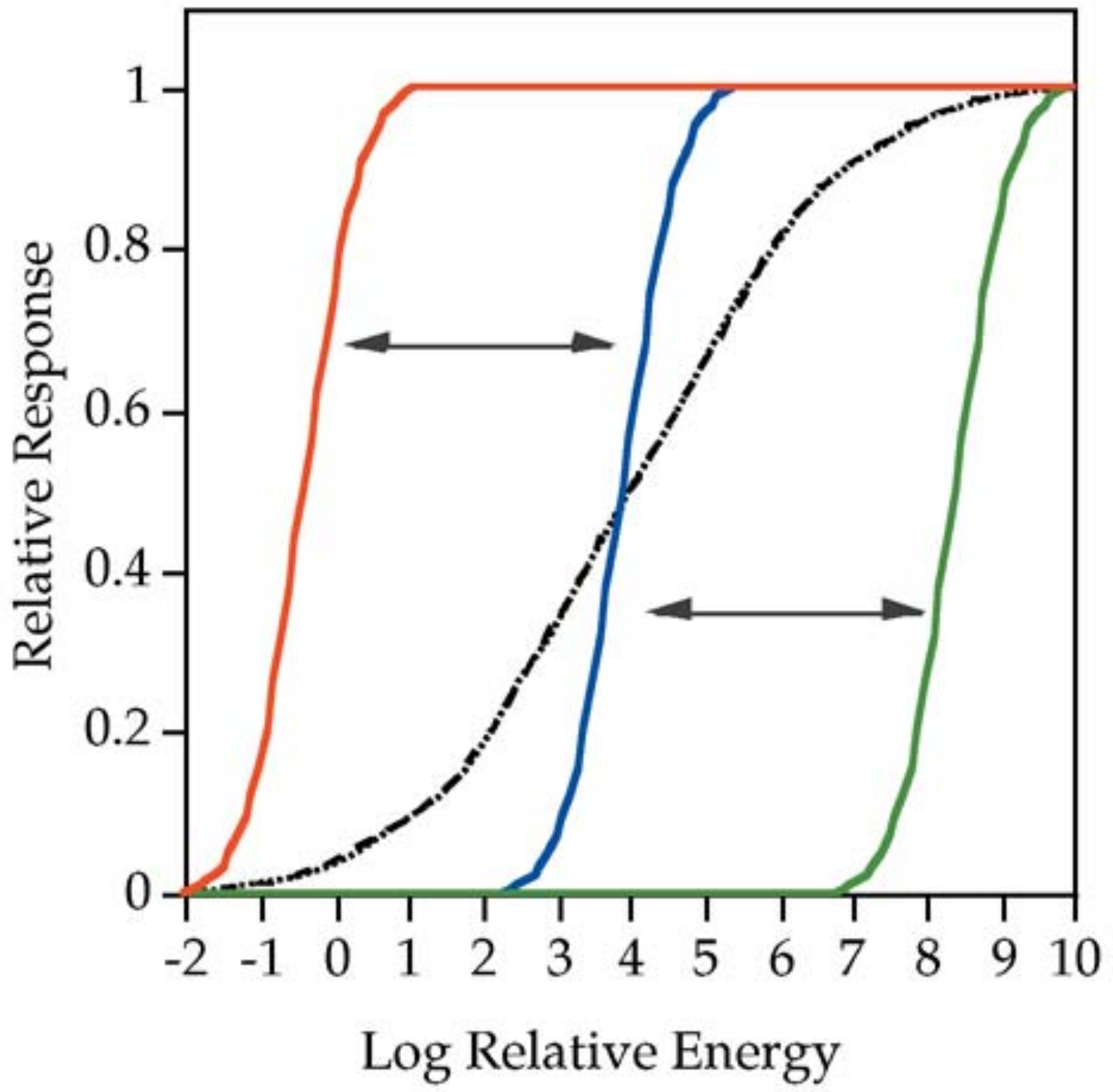
Cones and Rods

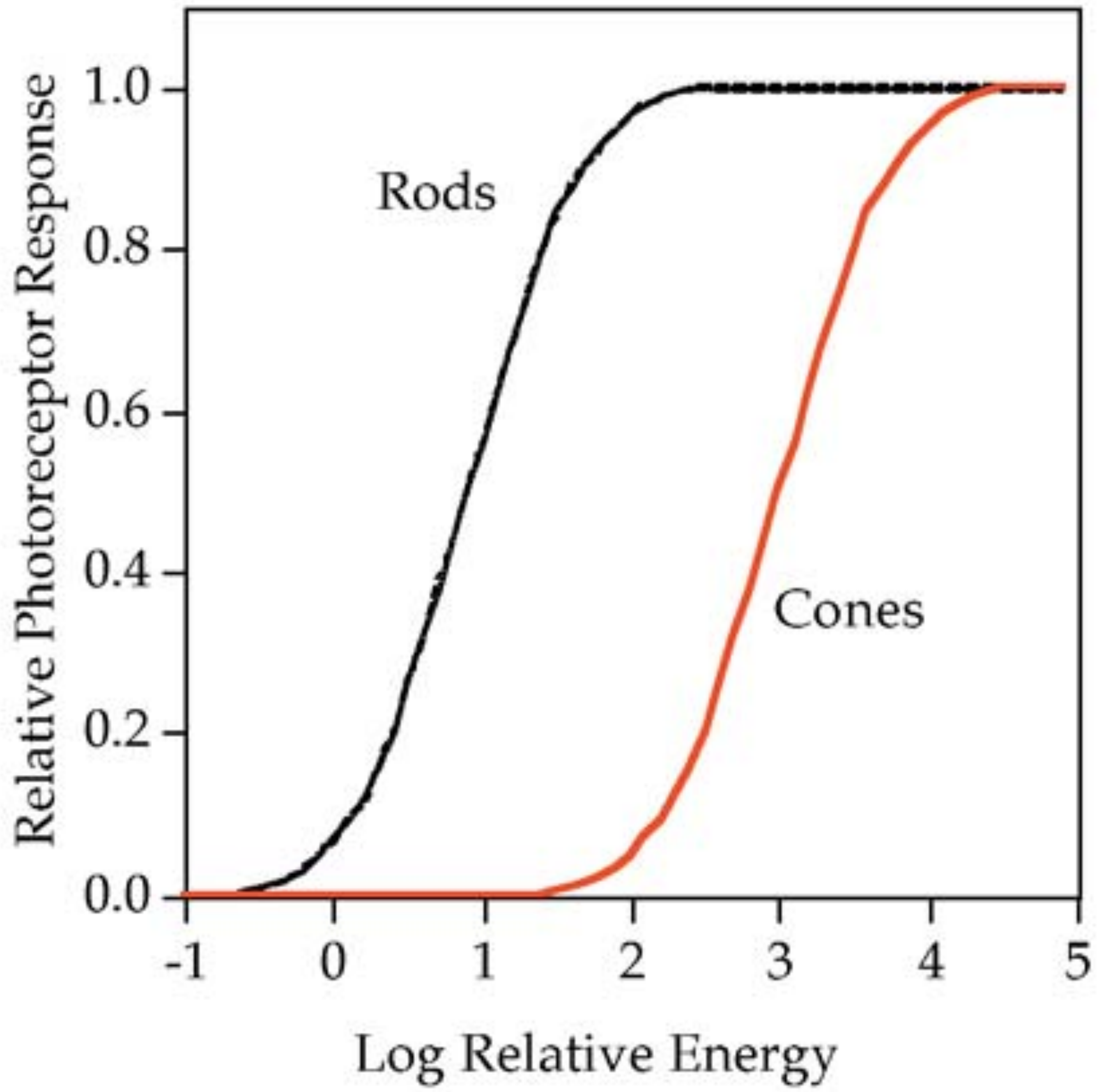


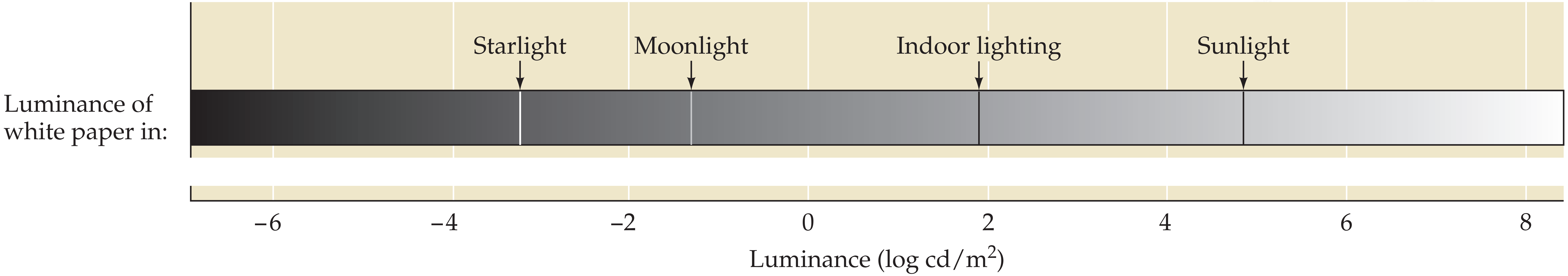


Shift in Response Increases Resolution

* note that it’s hard to quantify the magnitude of behavioral responses, unlike neural responses







Purves et al. Neuroscience 6ed; Fairchild, Color Appearance Models, 2ed

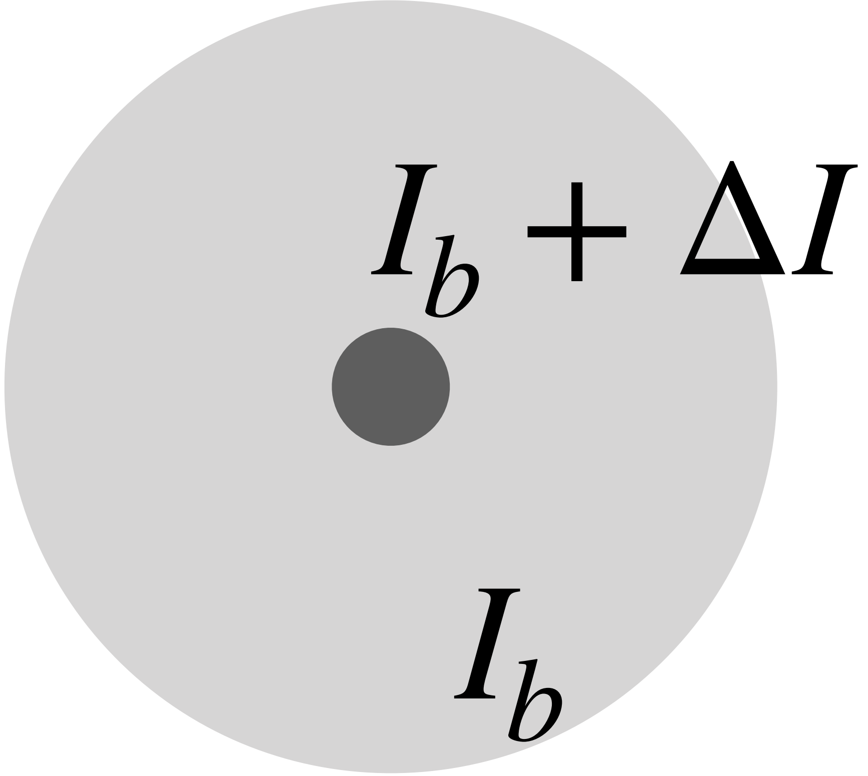
How Does Our Vision Desensitize?

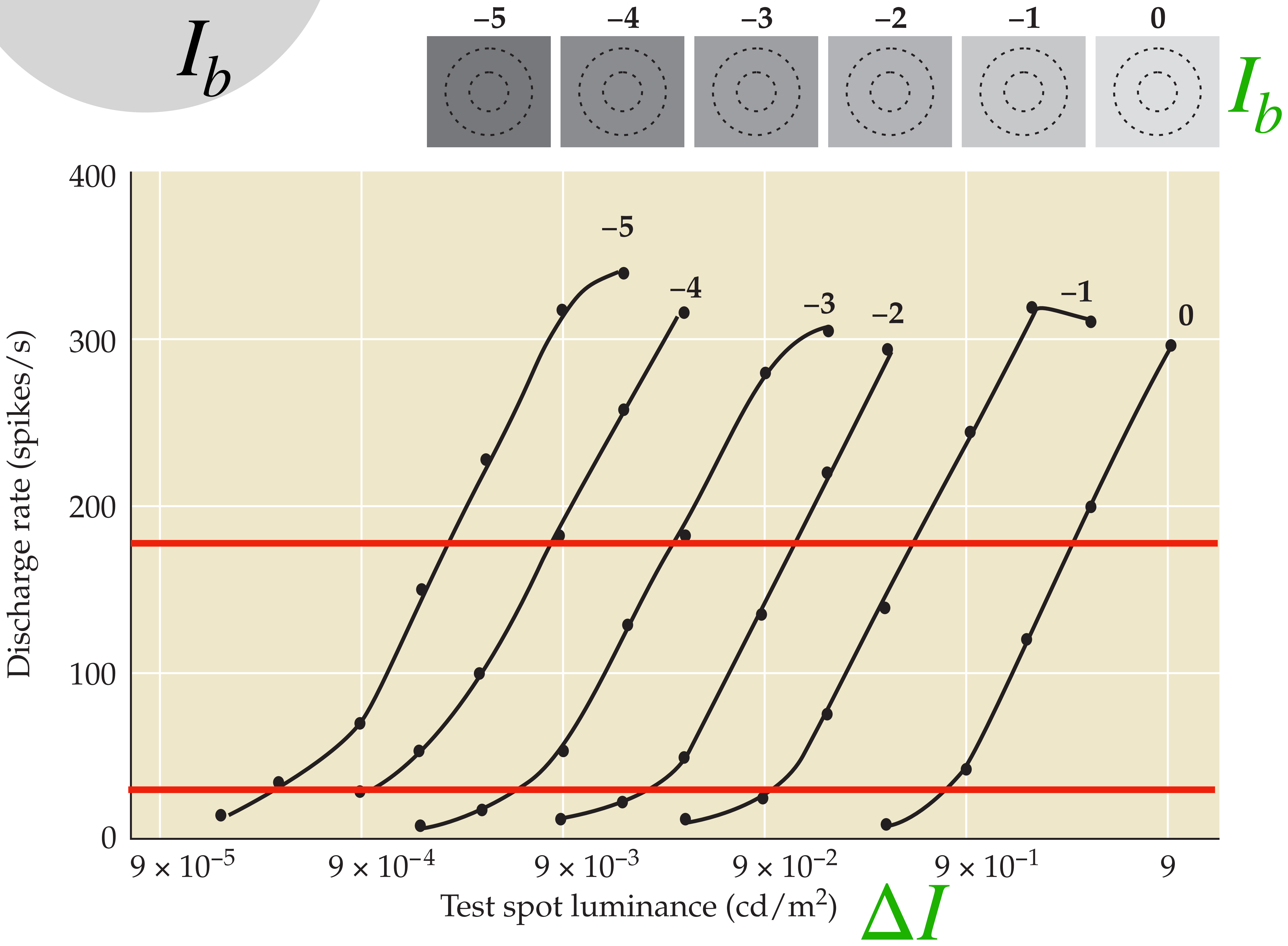
- Pupil size change
  - The pupil diameter ranges from 1 or 2 mm to about 8 mm, for an increase in area (or total light entering the eye) of a factor of 16-64
  - For light adaptation, as light level increases pupil size reduces, which requires more intense flashes to evoke the same level of response
- Switch over between cones and rods
- The cells themselves also become desensitized
  - We will look at the RGCs and photoreceptors

RGC Desensitization

Response vs. Intensity

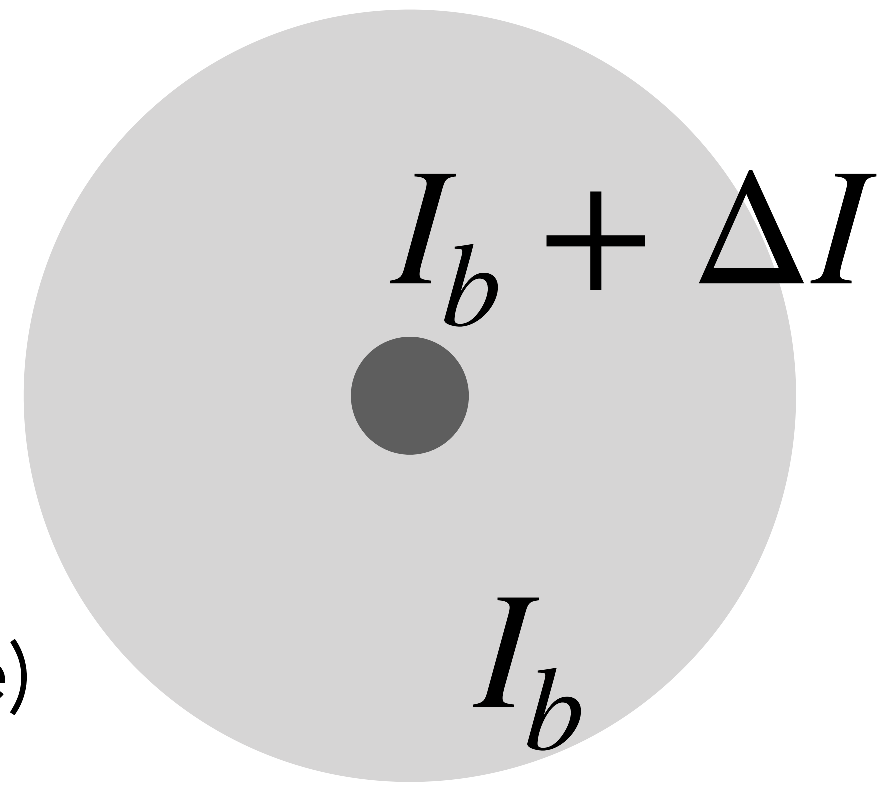
- RGCs use a small dynamic range to reliably signal contrast information across a much wider dynamic range in ambient light level.
- Another perspective:
  - stronger signal is needed at high light level to produce a criterion level of RGC response.
  - "Desensitization"



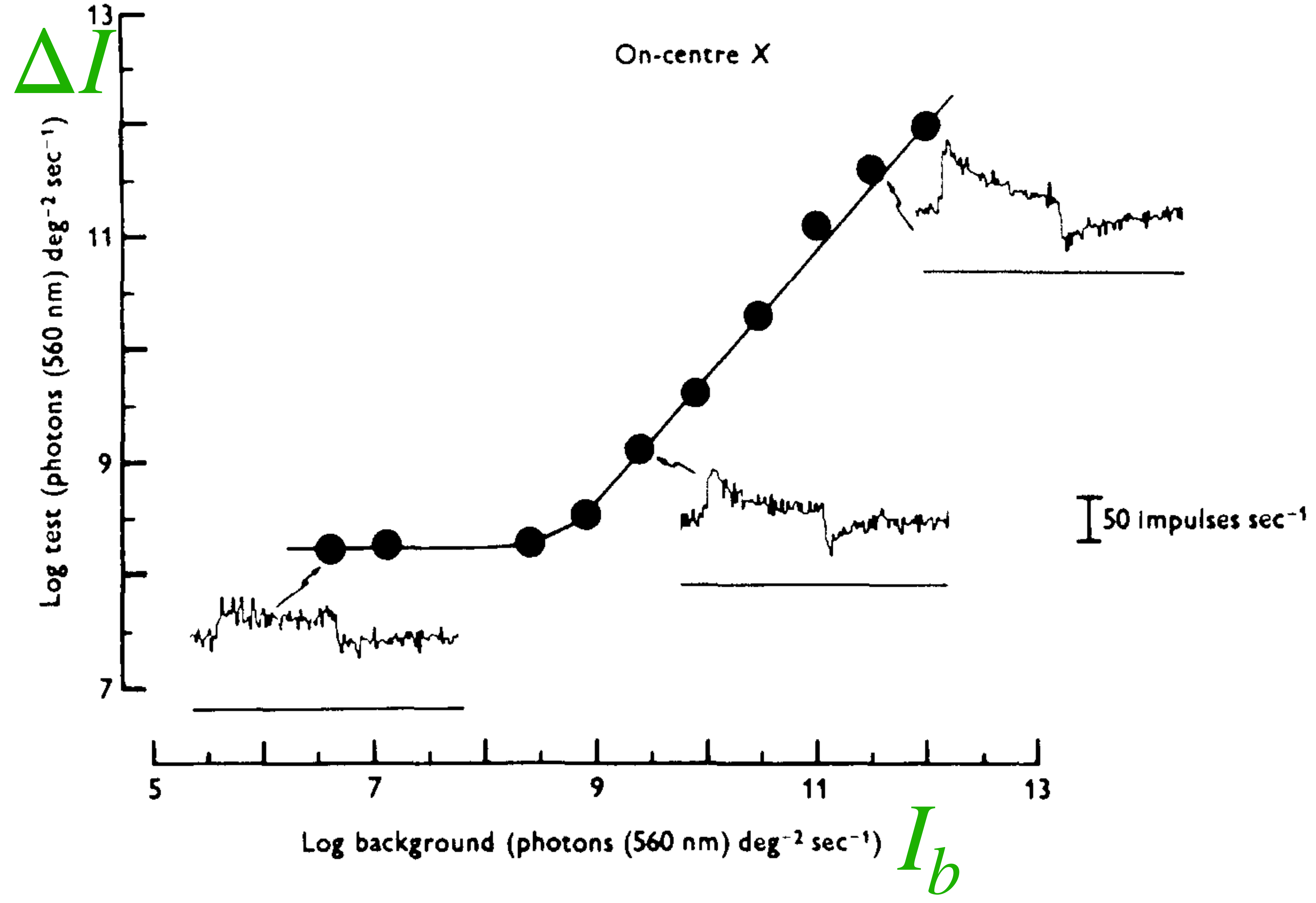


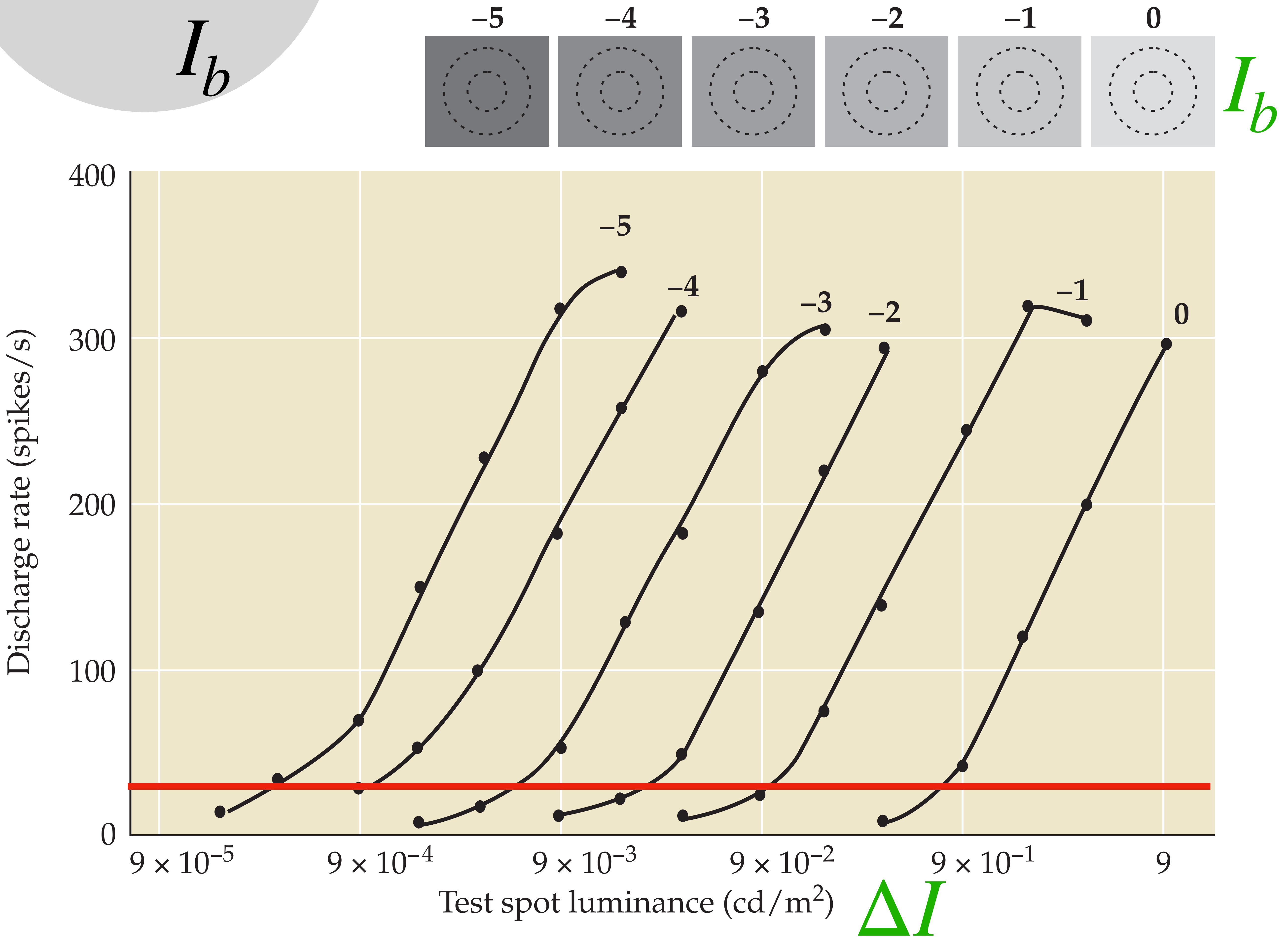
Purves et al. Neuroscience 6ed; Sakmann and Creutzfeldt 1969

RGC Desensitization



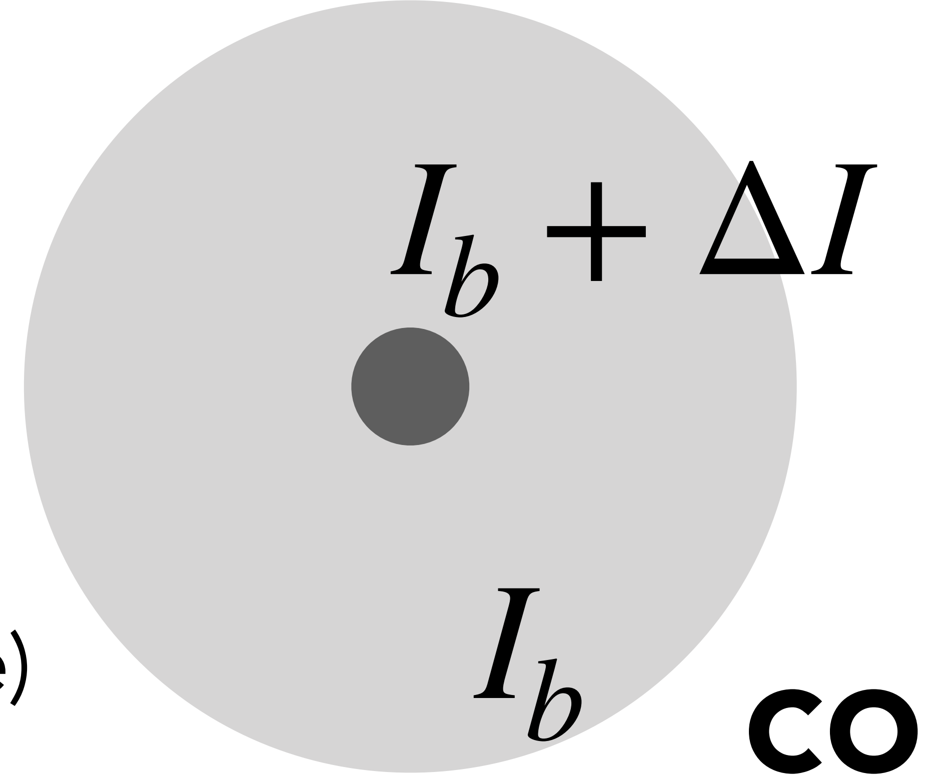
Plots the test light intensity (y-axis) that's needed to produce a criterion level RGC response (35 spikes/s here) under different background light intensities (x-axis)





Purves et al. Neuroscience 6ed; Sakmann and Creutzfeldt 1969; Enroth-Cugell et al., 1977;

RGC Desensitization



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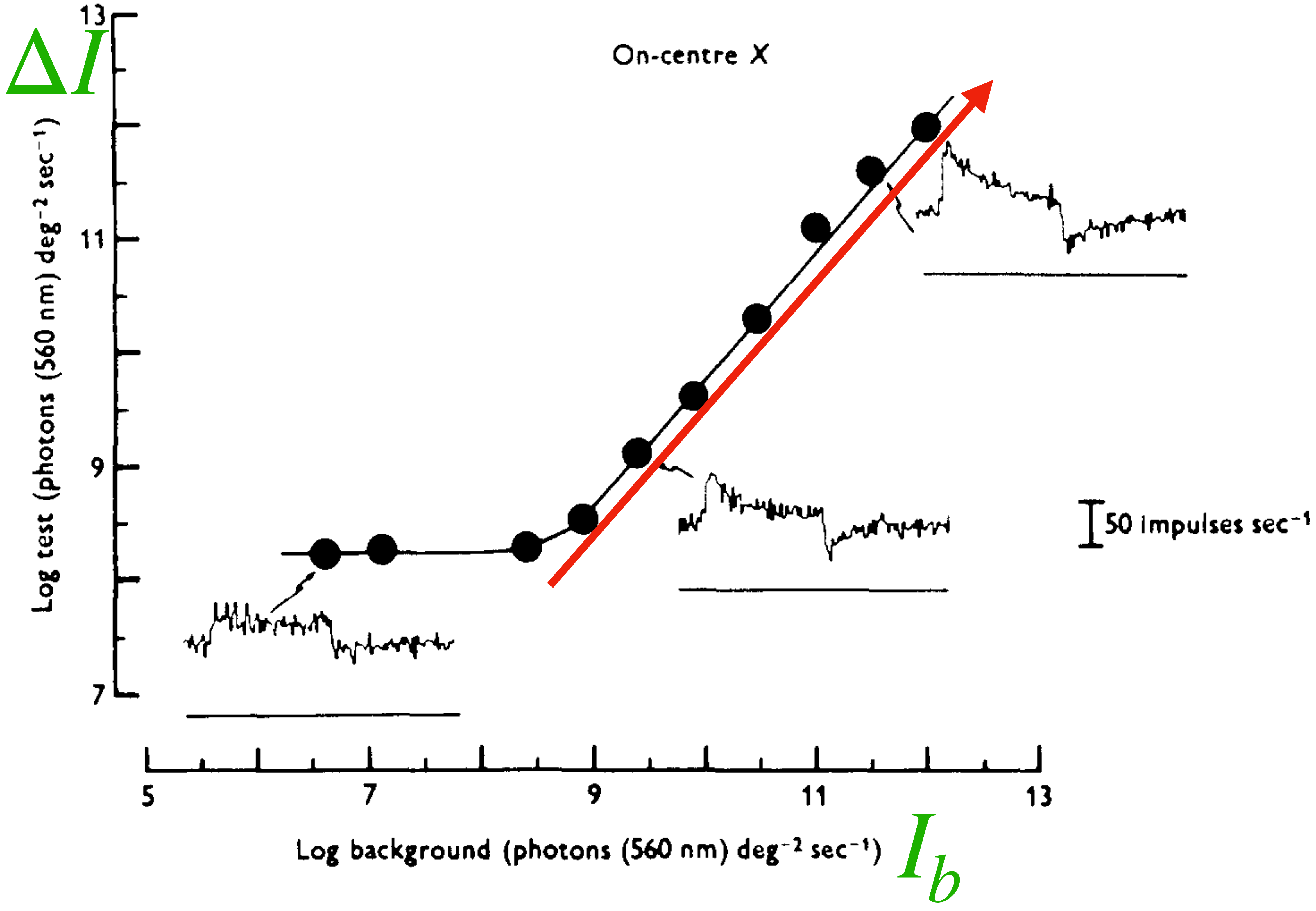


cat RGC

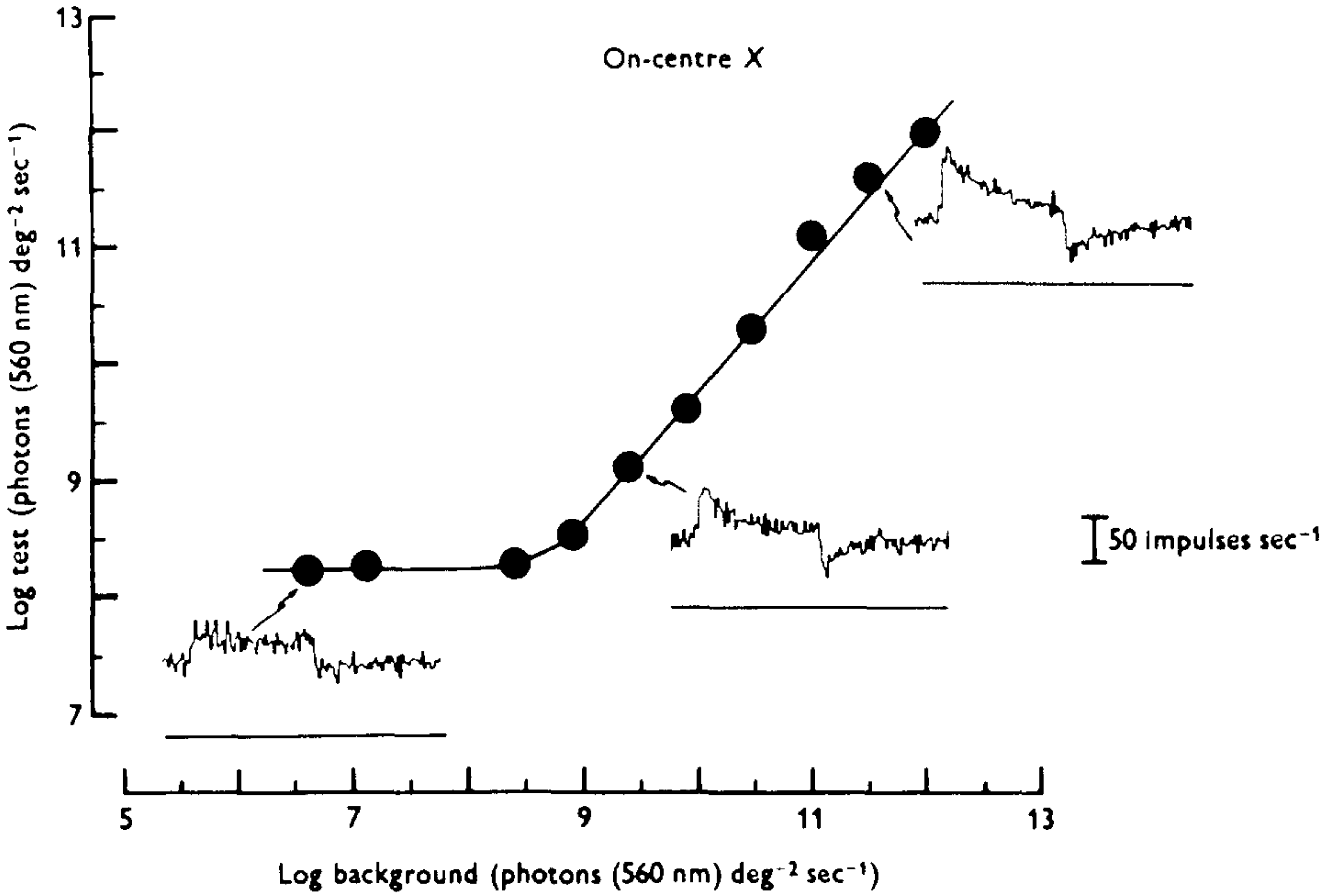
$$\textbf{contrast} = \frac{\Delta I}{I_b} \approx \textbf{constant}$$

- **Over a wide range of illumination levels, the contrast needed to produce a criterion level of RGC response is constant.**
  - Assuming that the behavioral JND corresponds to a criterion level of RGC response.

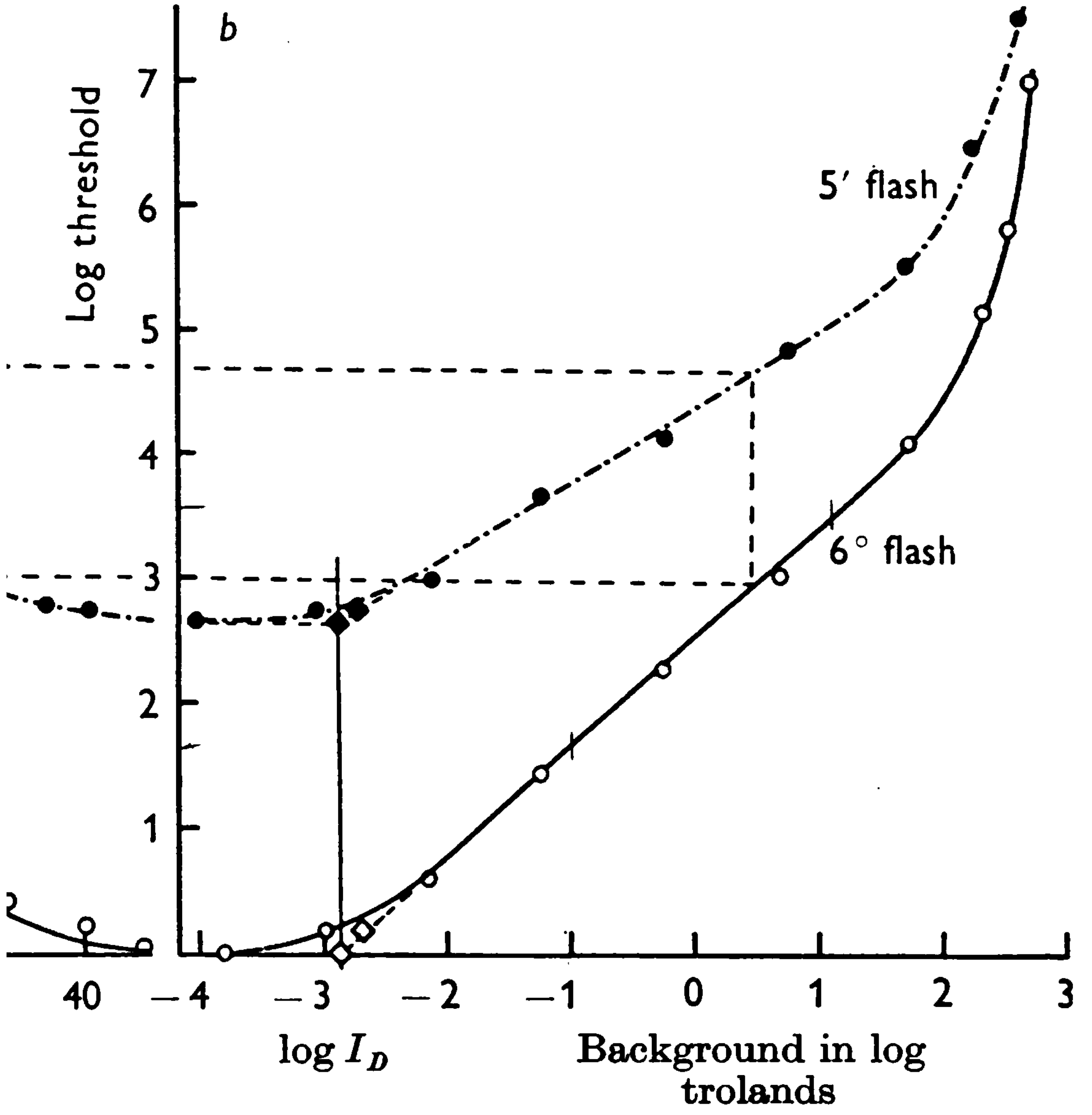
Purves et al. Neuroscience 6ed; Sakmann and Creutzfeldt 1969; Enroth-Cugell et al., 1977;

RGC and Human Behavioral Adaptations Match

Contrast needed to stimulate RGC is constant across background levels

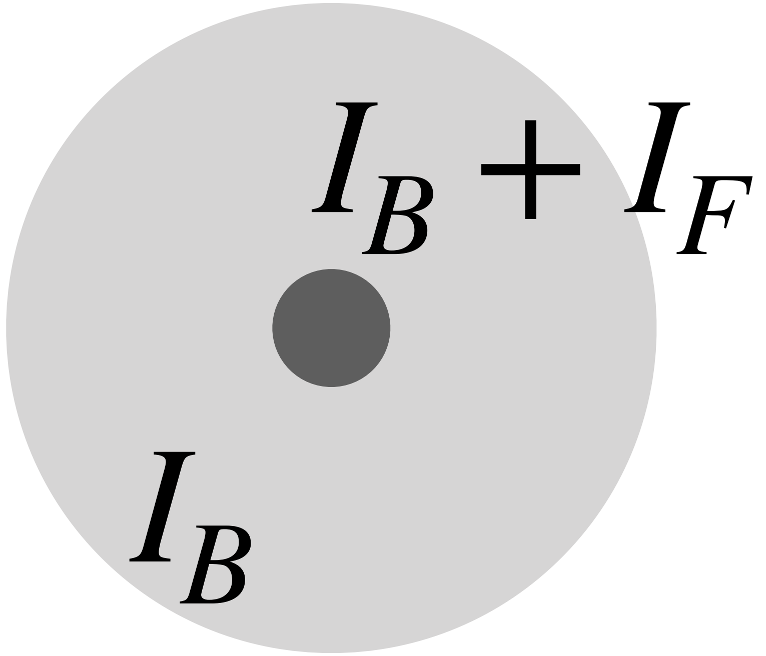


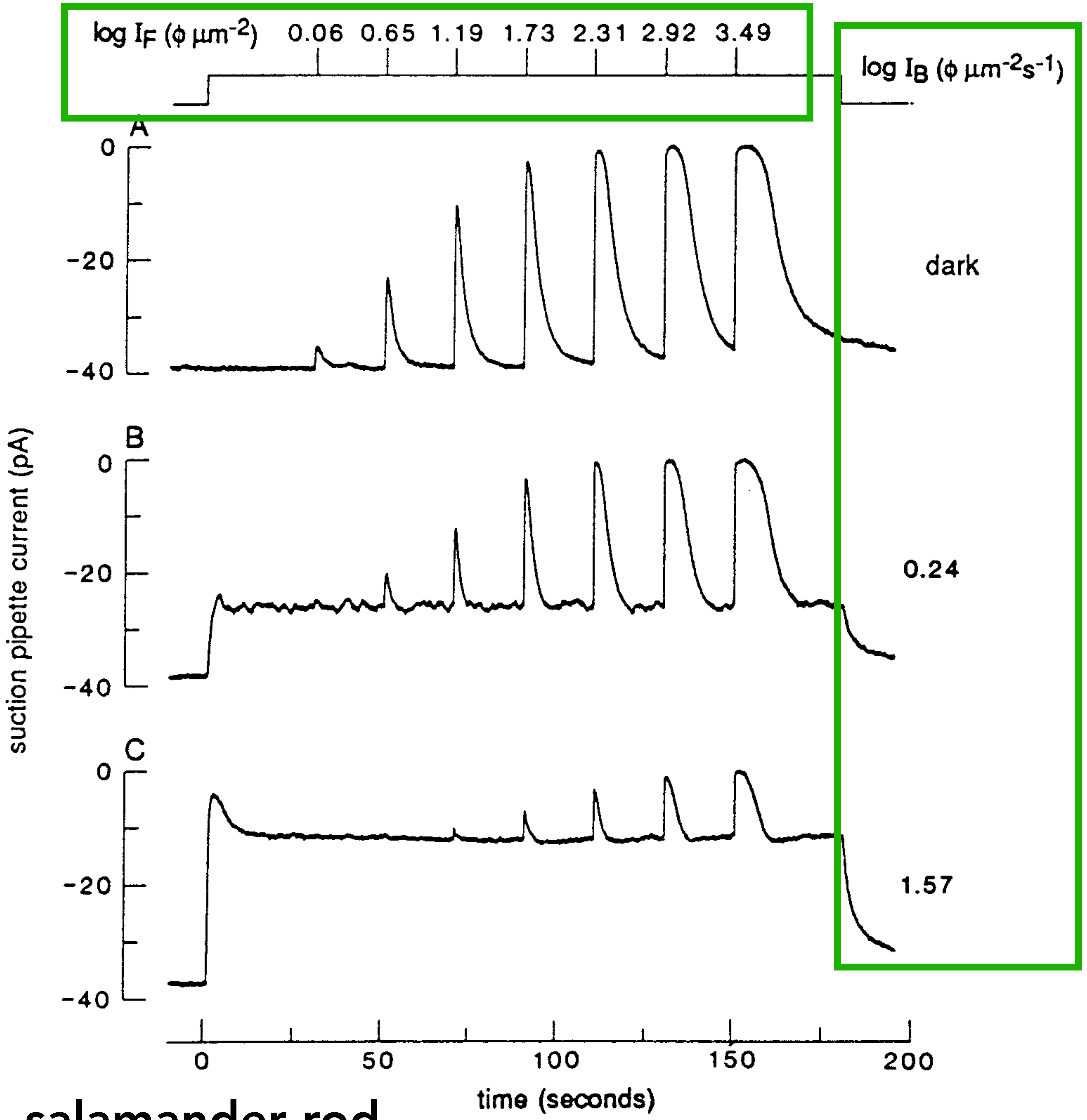
Constant needed to be noticeable by humans is constant across background levels



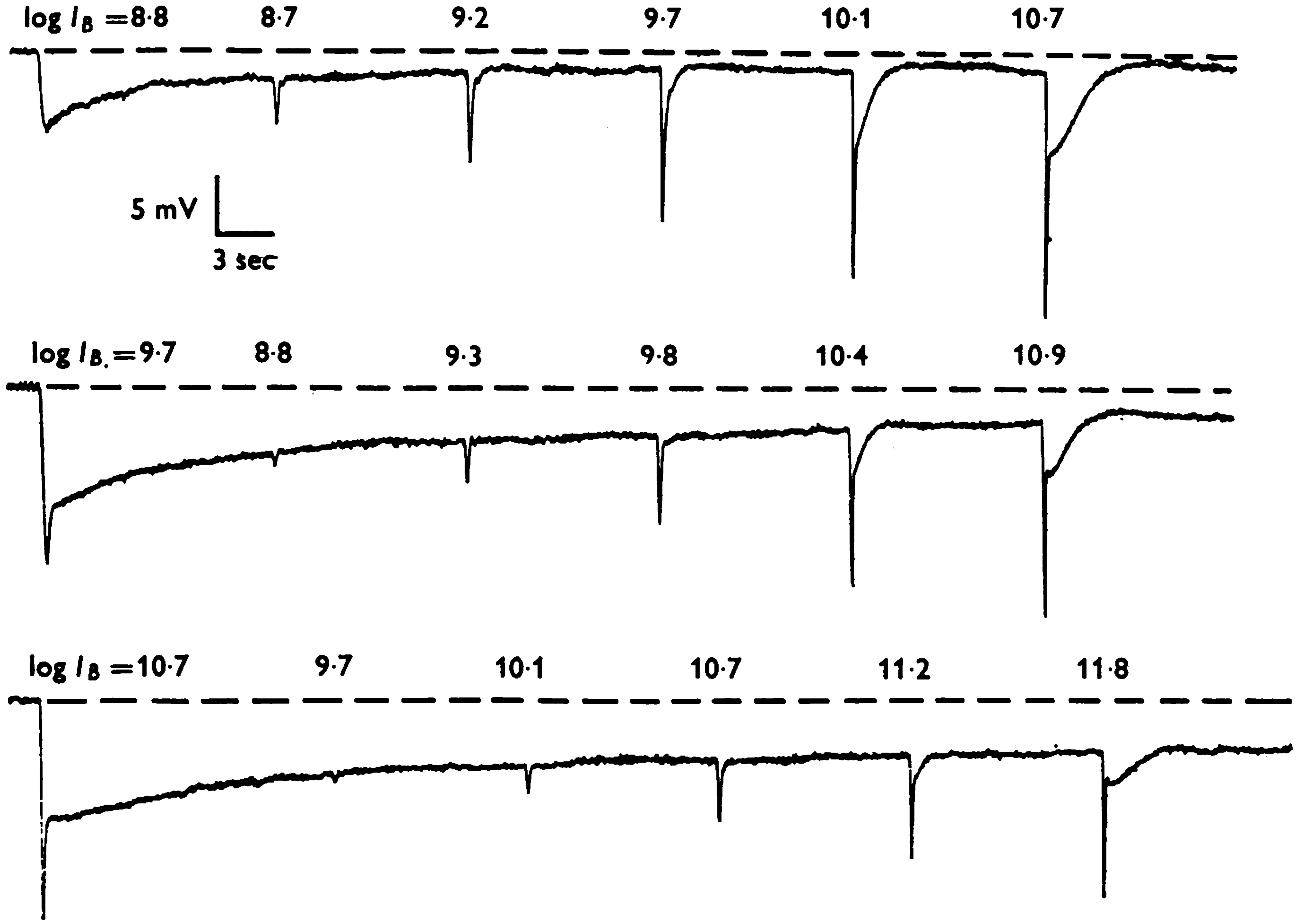
Enroth-Cugell et al., 1977; Blakemore & Rushton 1965

Photoreceptor Desensitization





salamander rod

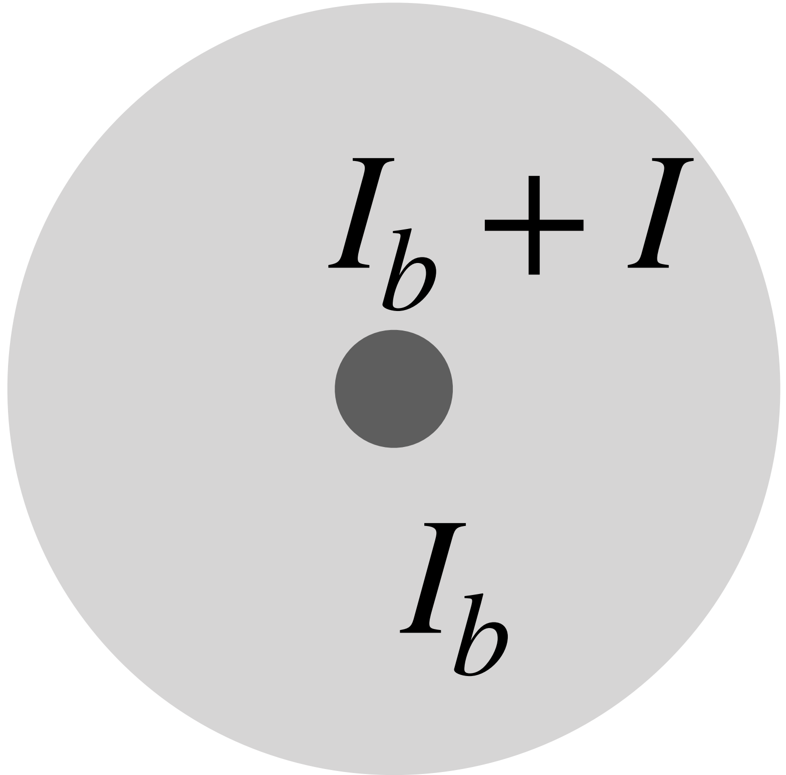


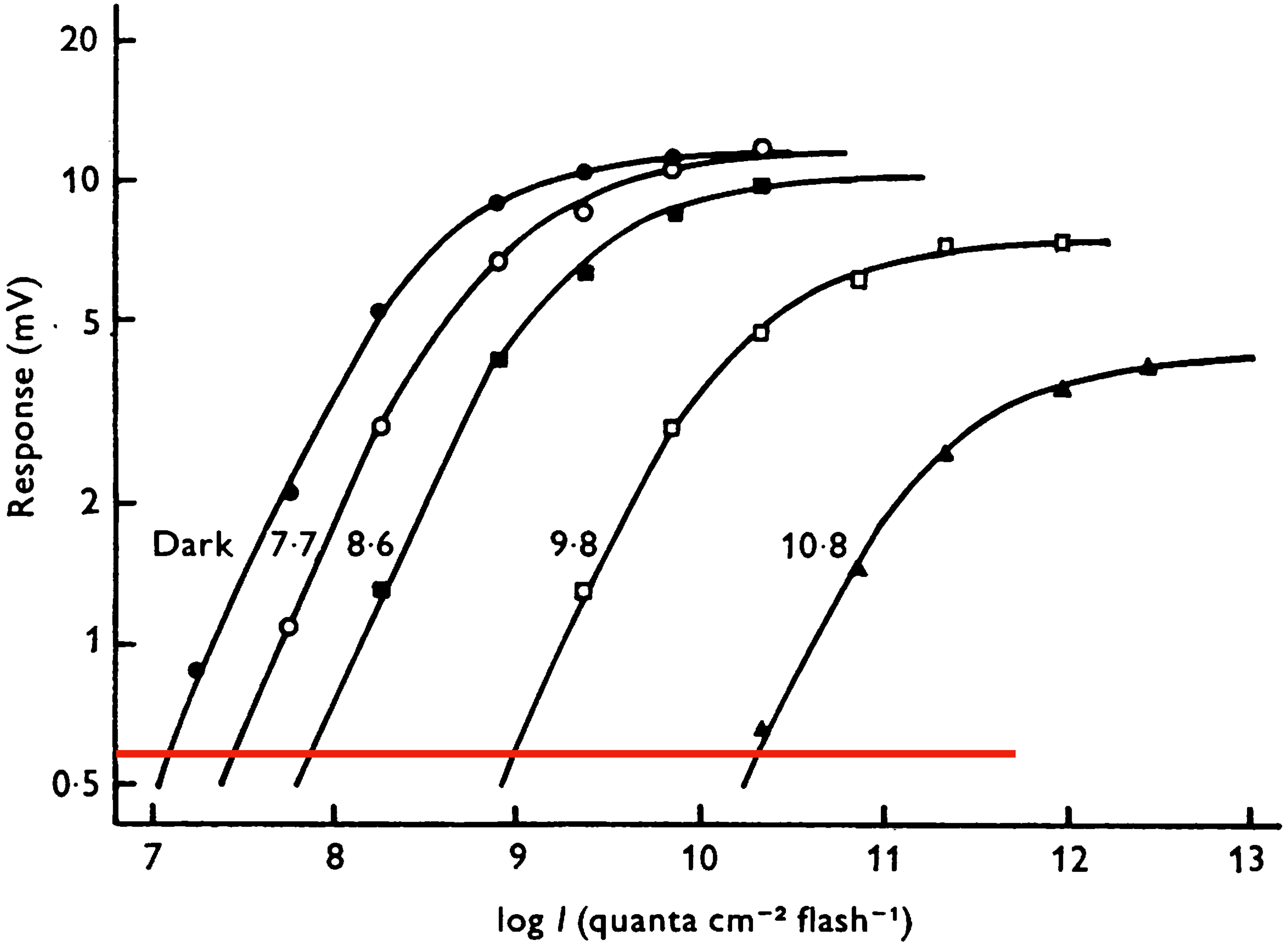
toad rod

Fain 1976; Fain 2001

Photoreceptor Desensitization

* toad rod



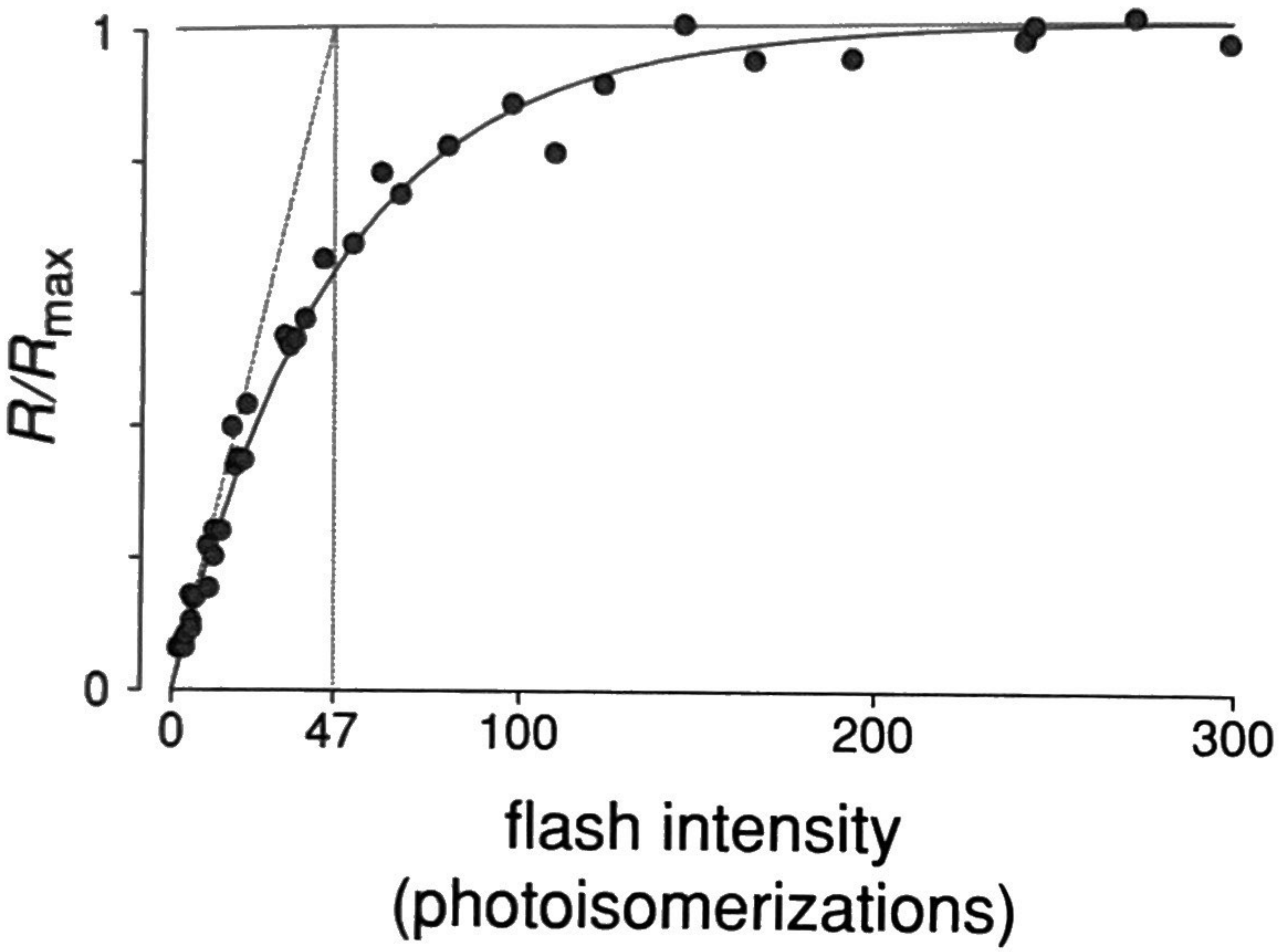


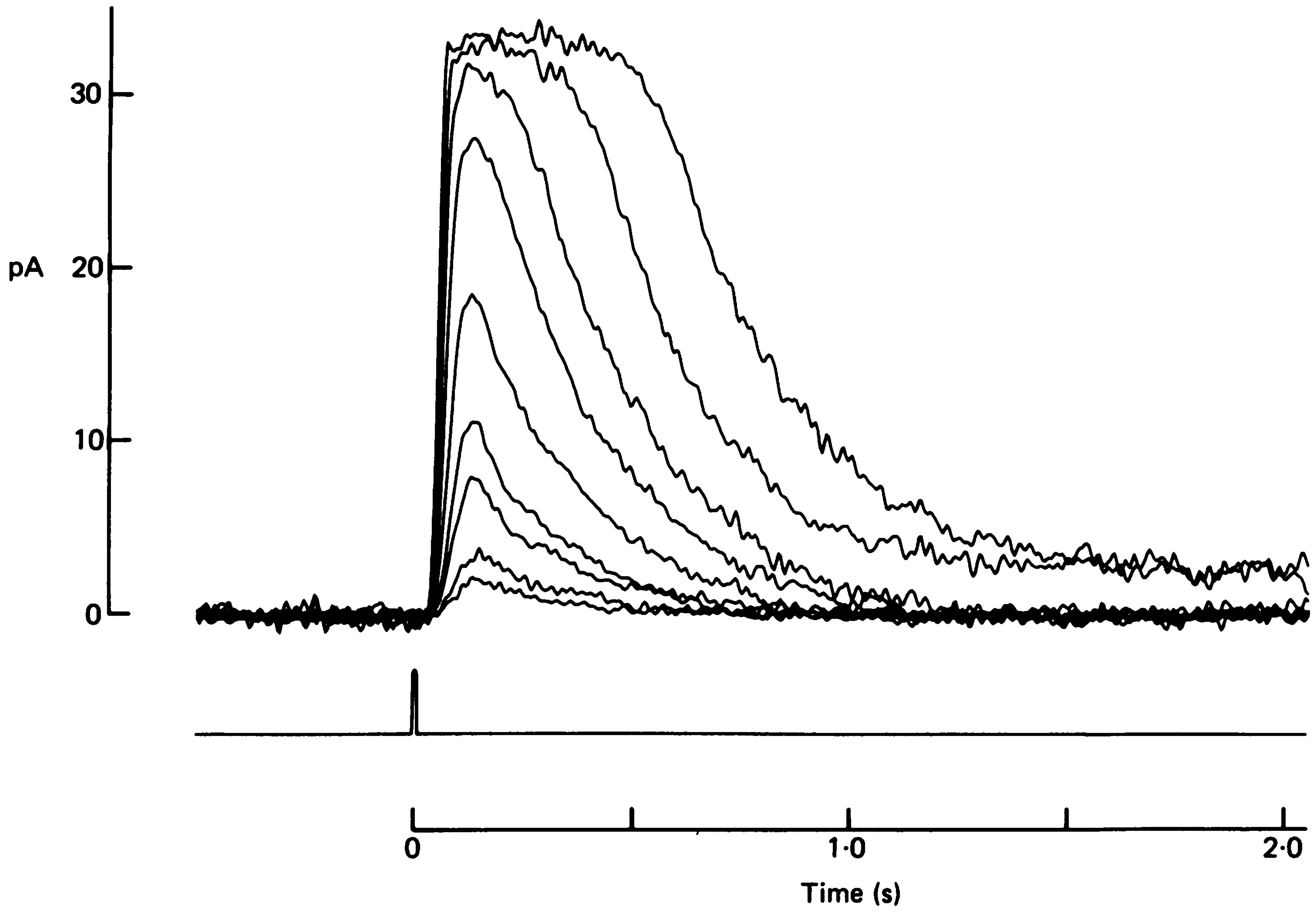
- Illuminant the photoreceptor at a given background level until the response settles
- Flash a spot light at the photoreceptor and measure the peak response vs. flash intensity

Fain, 1976

(Peak) Response vs. Flash Intensity

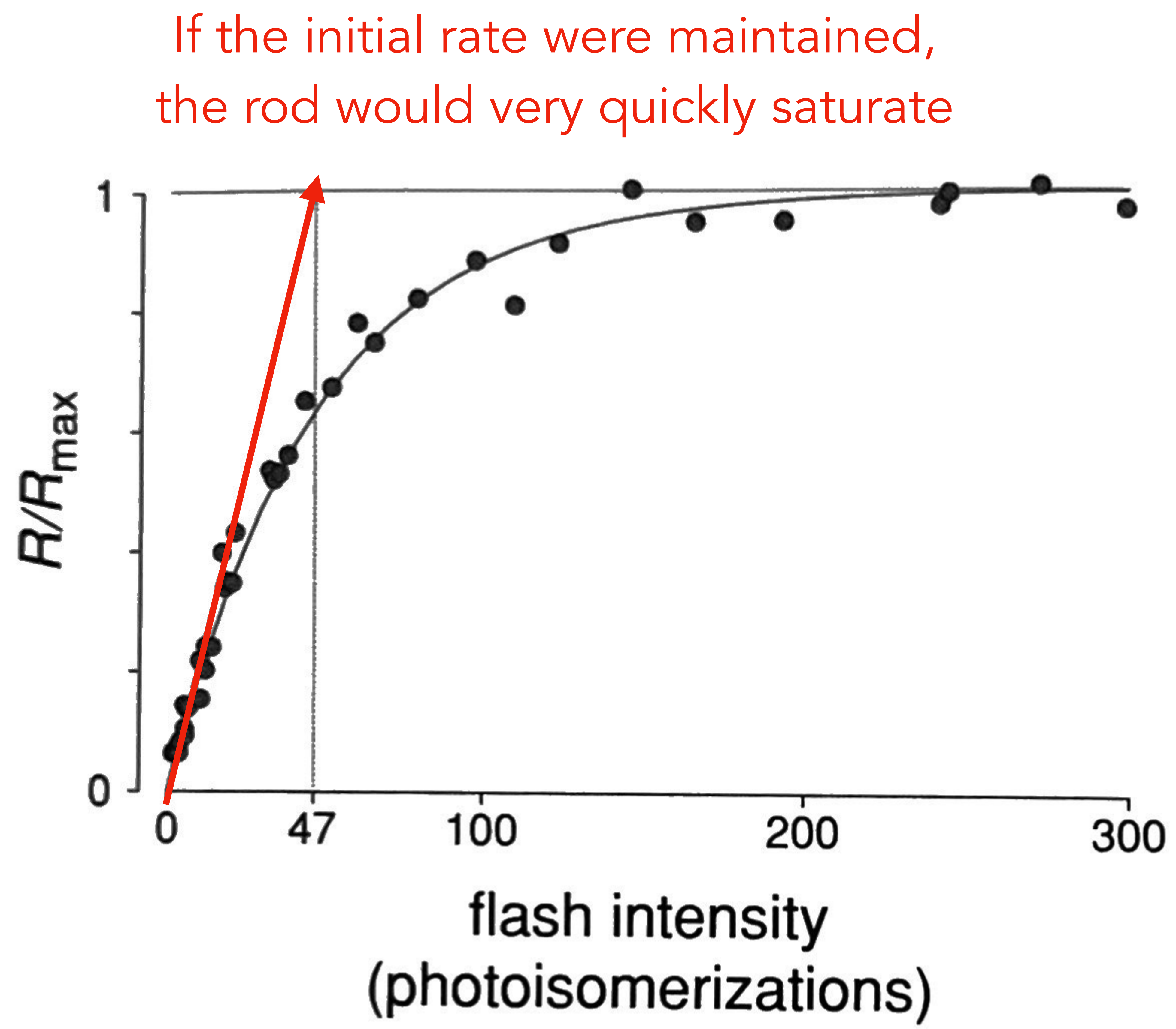
* Macaque rods





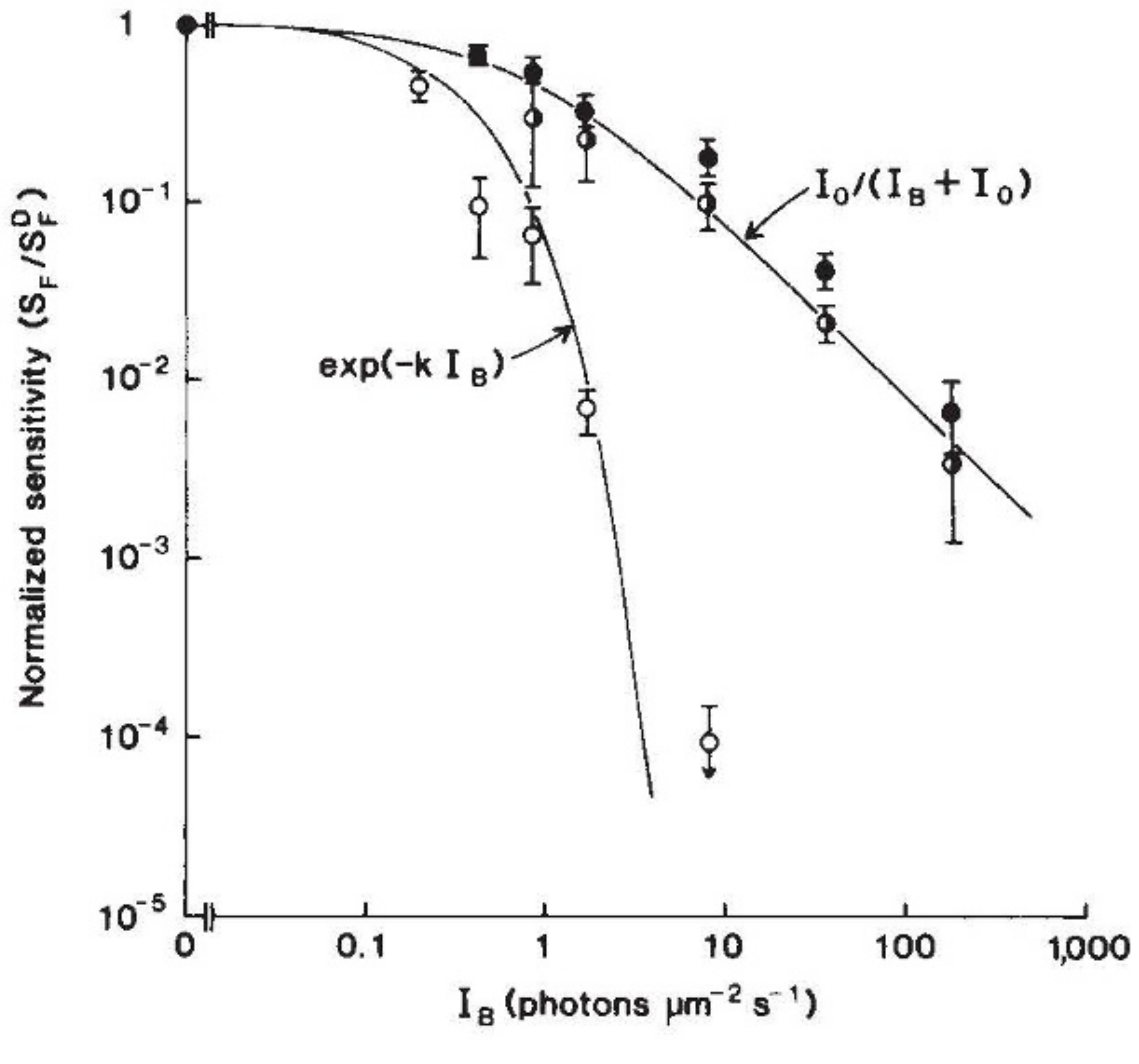
Baylor et al., 1984

(Peak) Response vs. Flash Intensity



- Electrical response vs. light intensity is not linear!
    - ~exponential saturation
    - as if the photoreceptor becomes less sensitive when light becomes more intensity: **desensitization**
    - essential for **adaptation**
    - This doesn't contradict the Principle of Univariance!

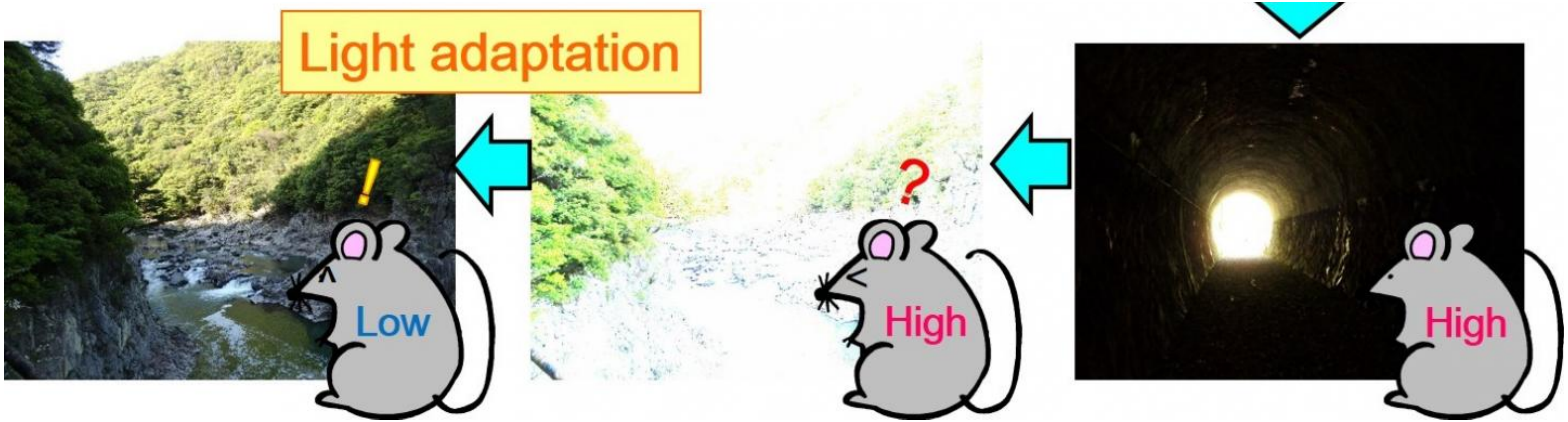
Why Do Photoreceptors Desensitize?



- As background light level increases, fewer pigments are available to absorb photons, so the absorption rate naturally reduces.
  - The probability a photon meets a pigment is proportional to the # of pigments available
  - This is a classic example of exponential decay
- The actual desensitization is slightly better than exponential decay
  - There are negative feedbacks in the dynamical system

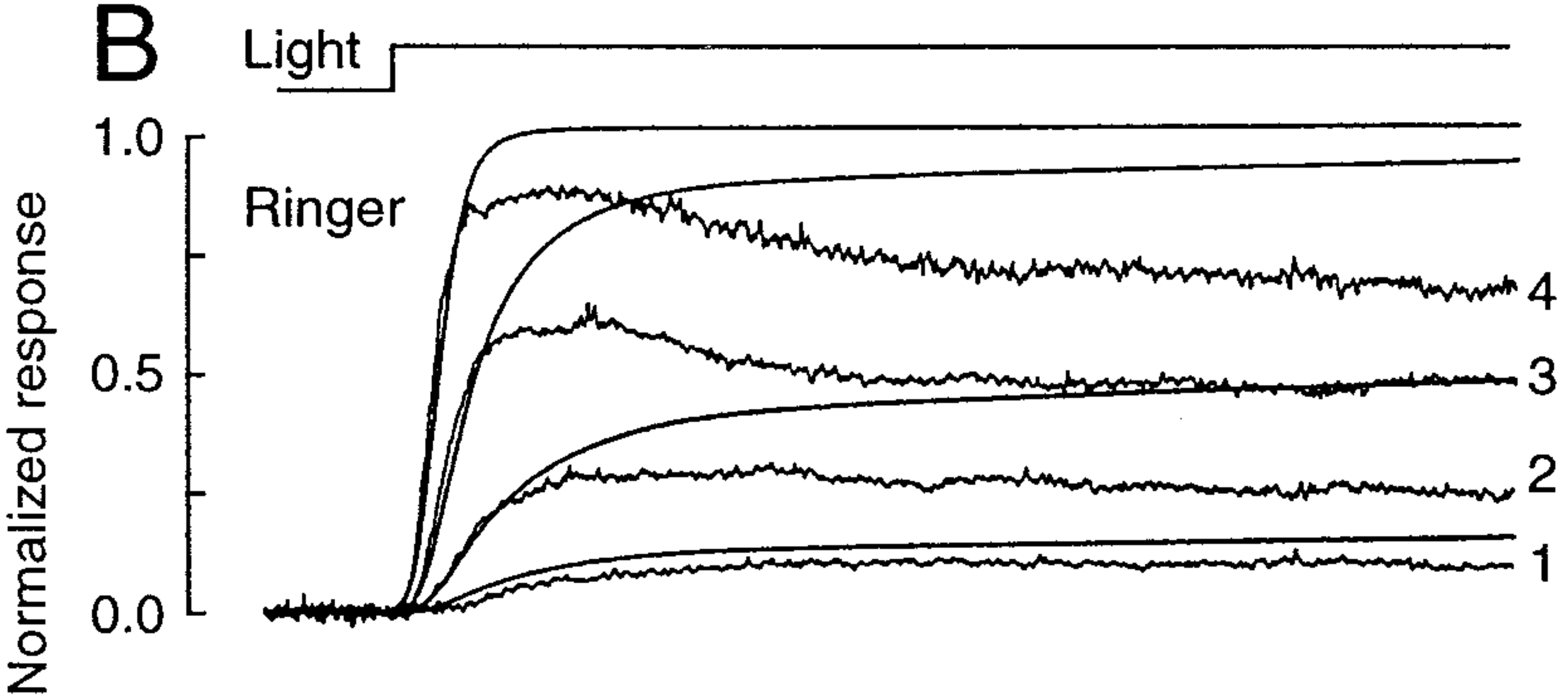
Matthews et al., 1998

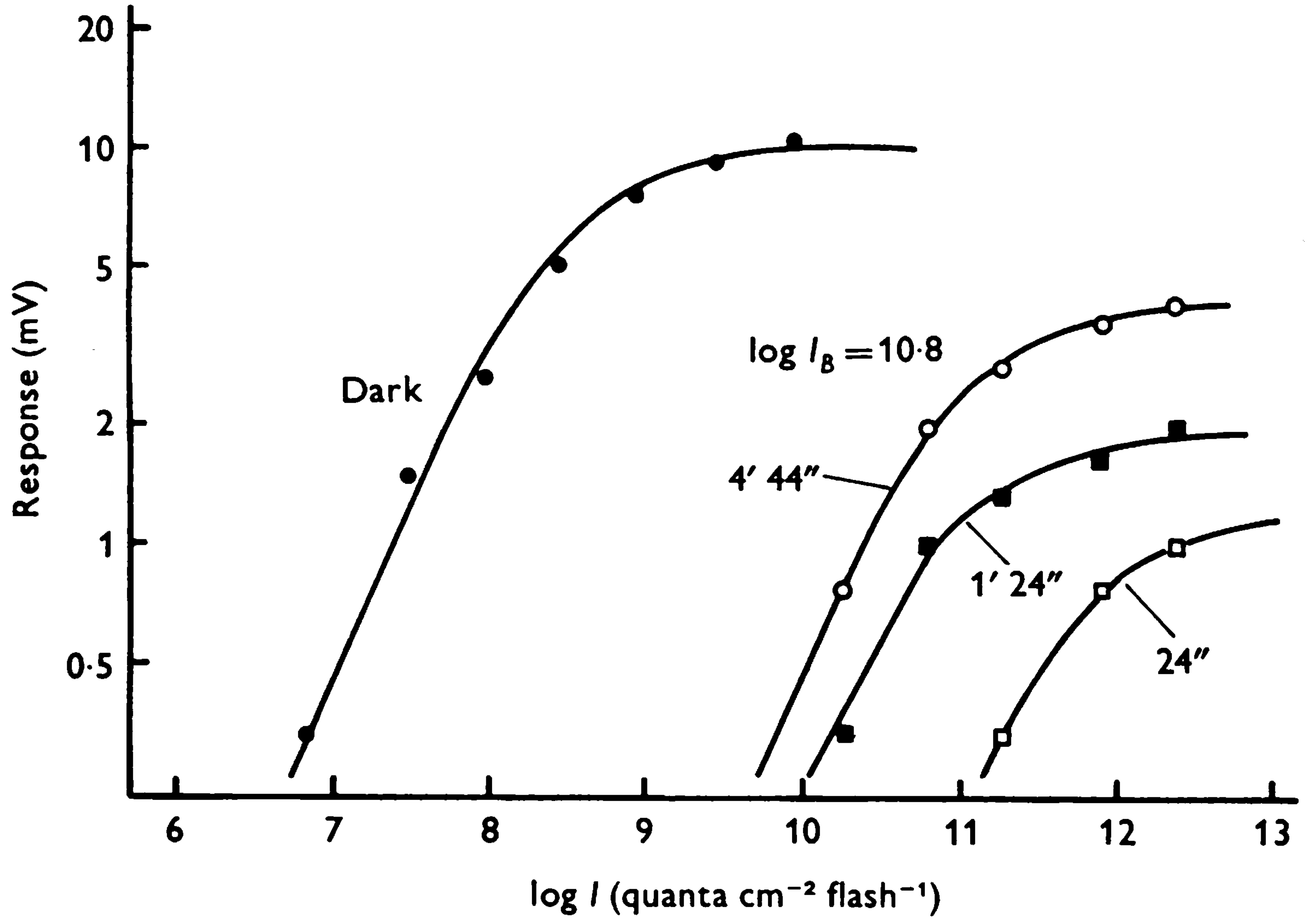
Partial Recovery of Visual Sensitivity



https://www.eurekalert.org/multimedia/883263

Photoreceptor Partial Recovery





Fain 1976; Fain 2001

Photoreceptor Partial Recovery

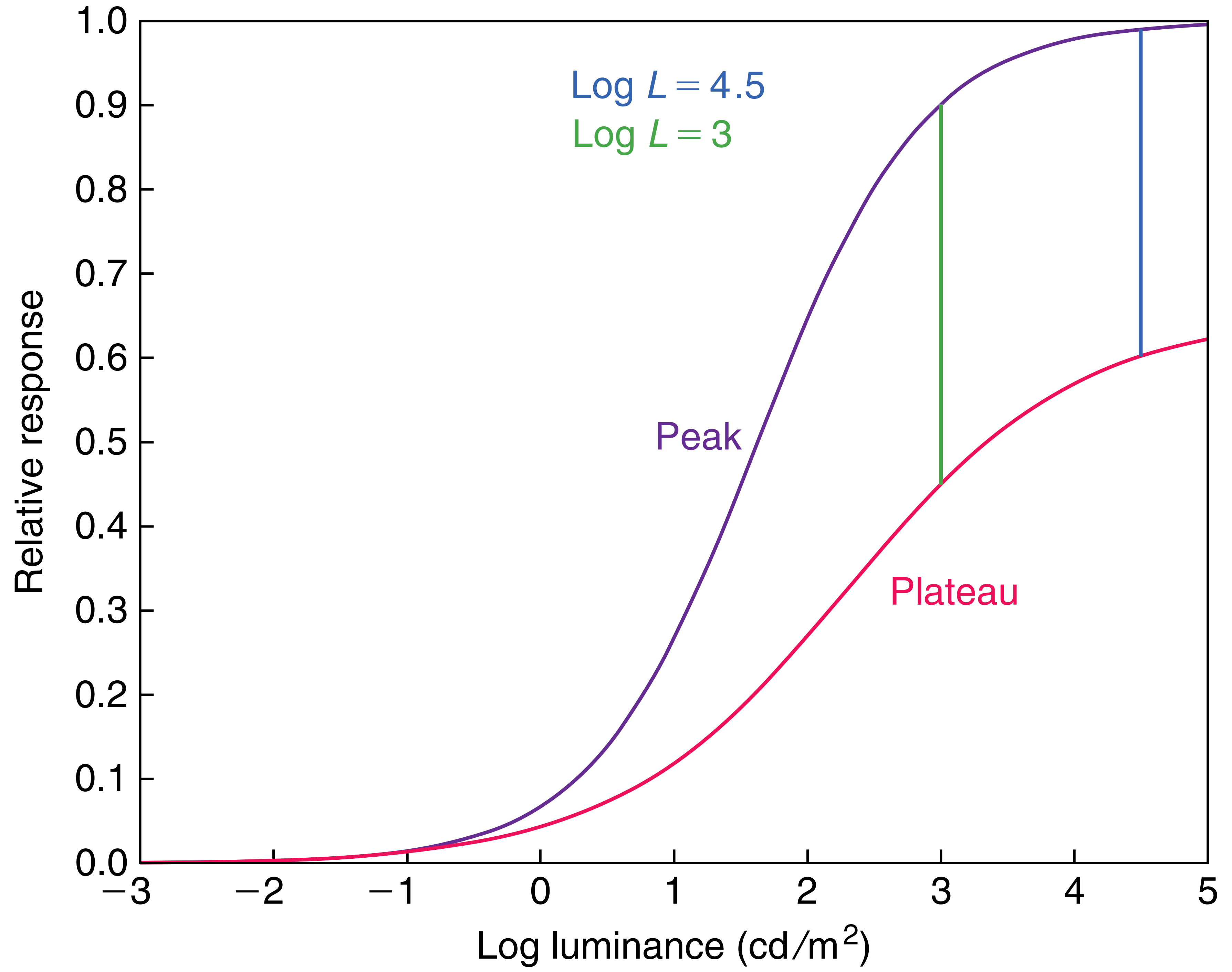


FIGURE 7.10 *Recovery of the response after a long exposure to background intensities [69].*

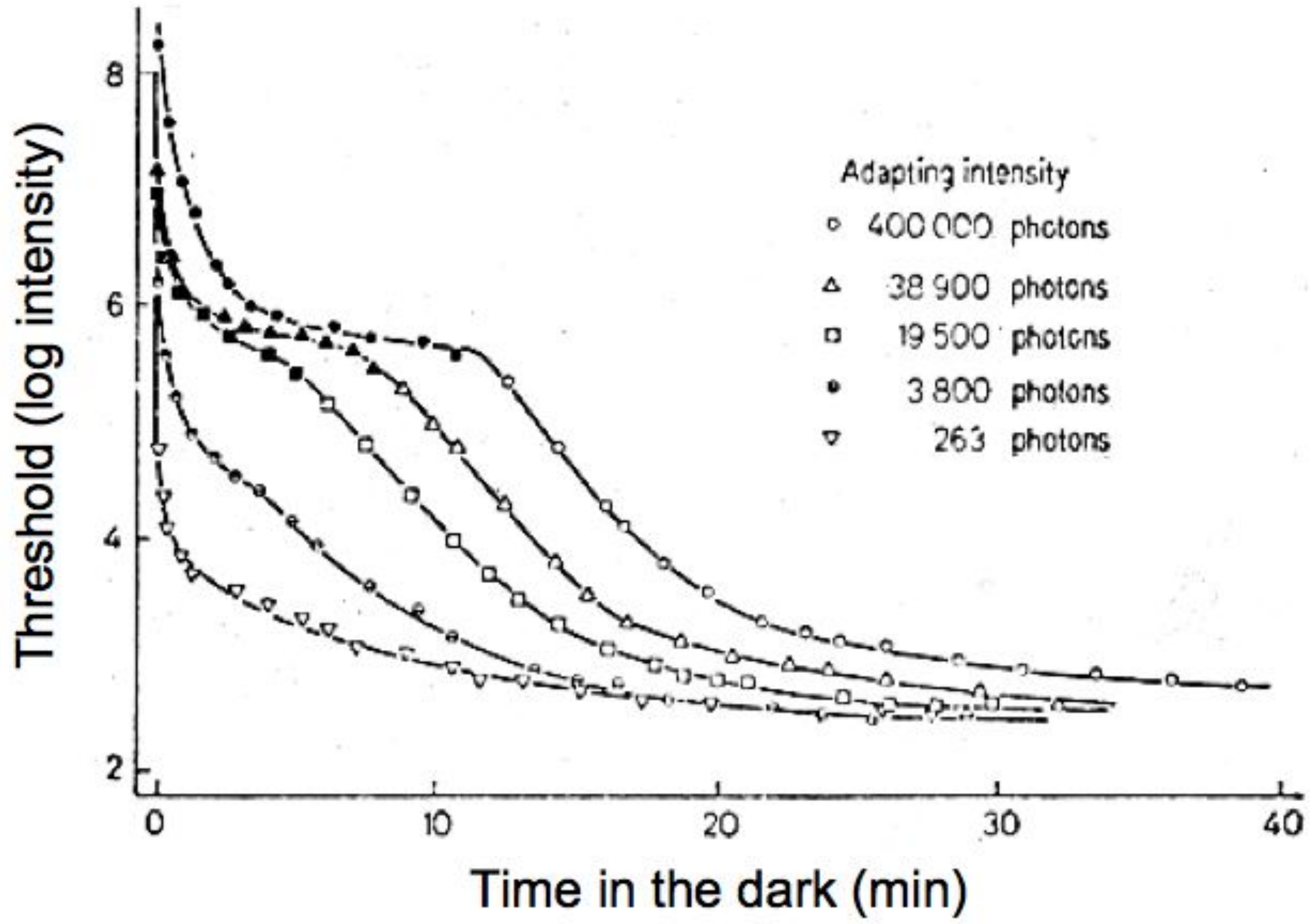
Reinhard et al. 2010

Dark Adaptation

Behavioral Phenomenon

https://www.eurekalert.org/multimedia/883263

Psychophysics



- Expose a participant to a particular intensity level
- Remove the light, and periodically
  - Flash a spot light in the dark
  - Measure the minimal spot light intensity needed for it to be detectable
  - Plot the threshold vs. time
- Switching from cones to rods leads to the bi-phasic curves

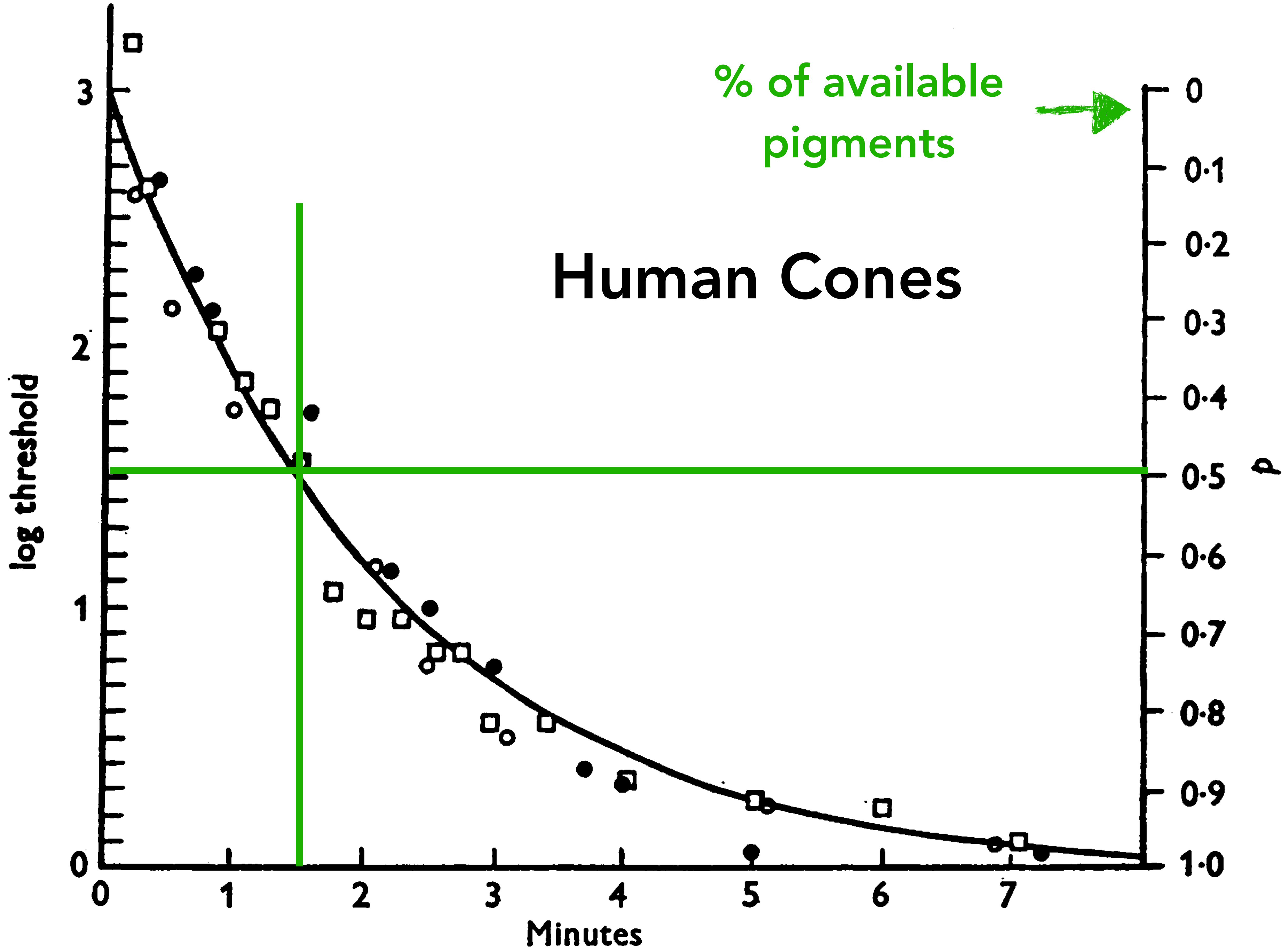
https://www.cns.nyu.edu/~david/courses/perception/lecturenotes/light-adapt/light-adapt.html

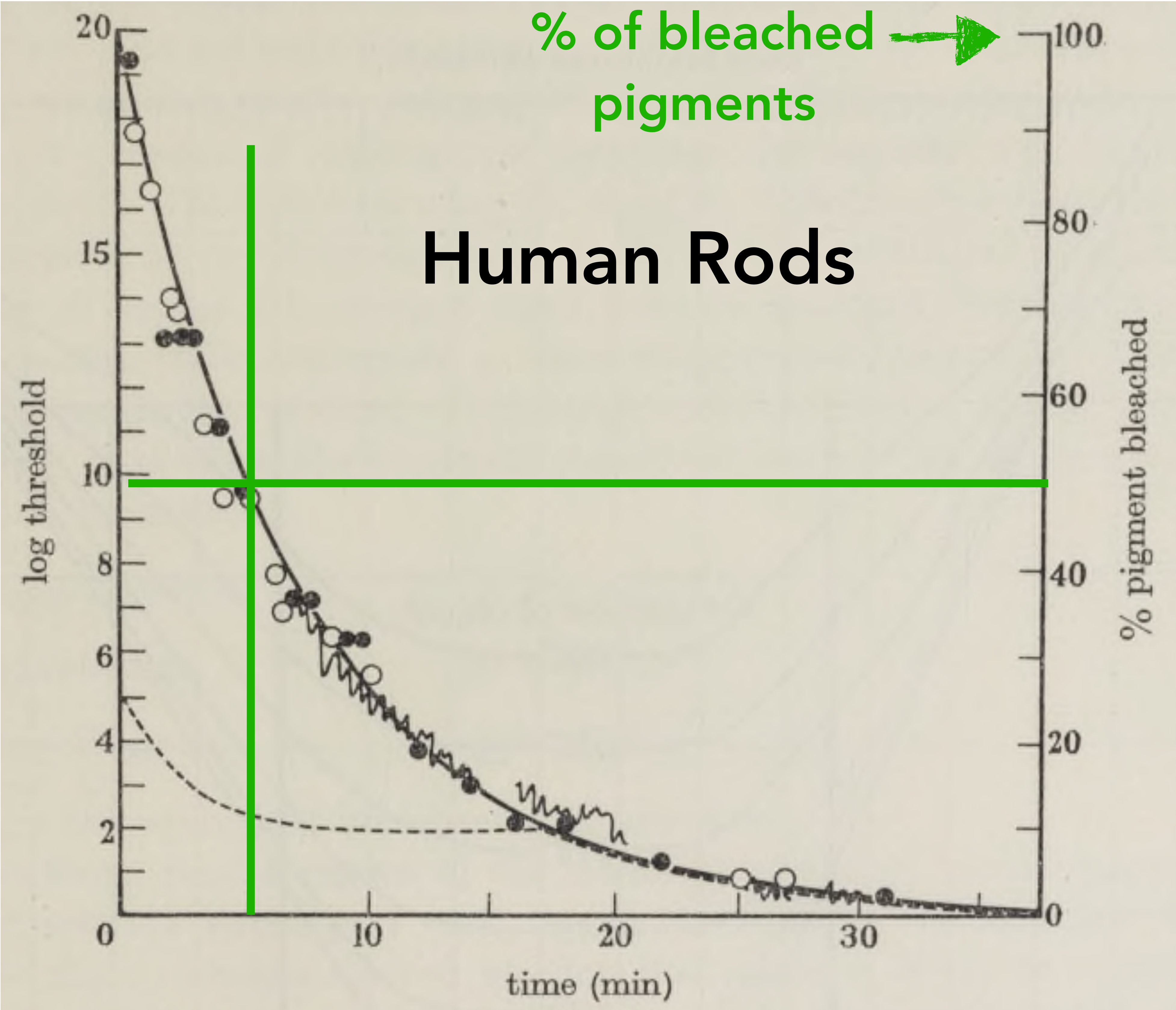
Mechanisms

- Pupil size change
- Photopigment re-generation
  - Photopigments are bleached when exposed to light and are constantly being re-generated. At a stable background light level, generation rate matches that the bleach rate.
  - When we remove light, no bleaching only regeneration. As more pigments are regenerated, our visual sensitivity increases (threshold reduces).

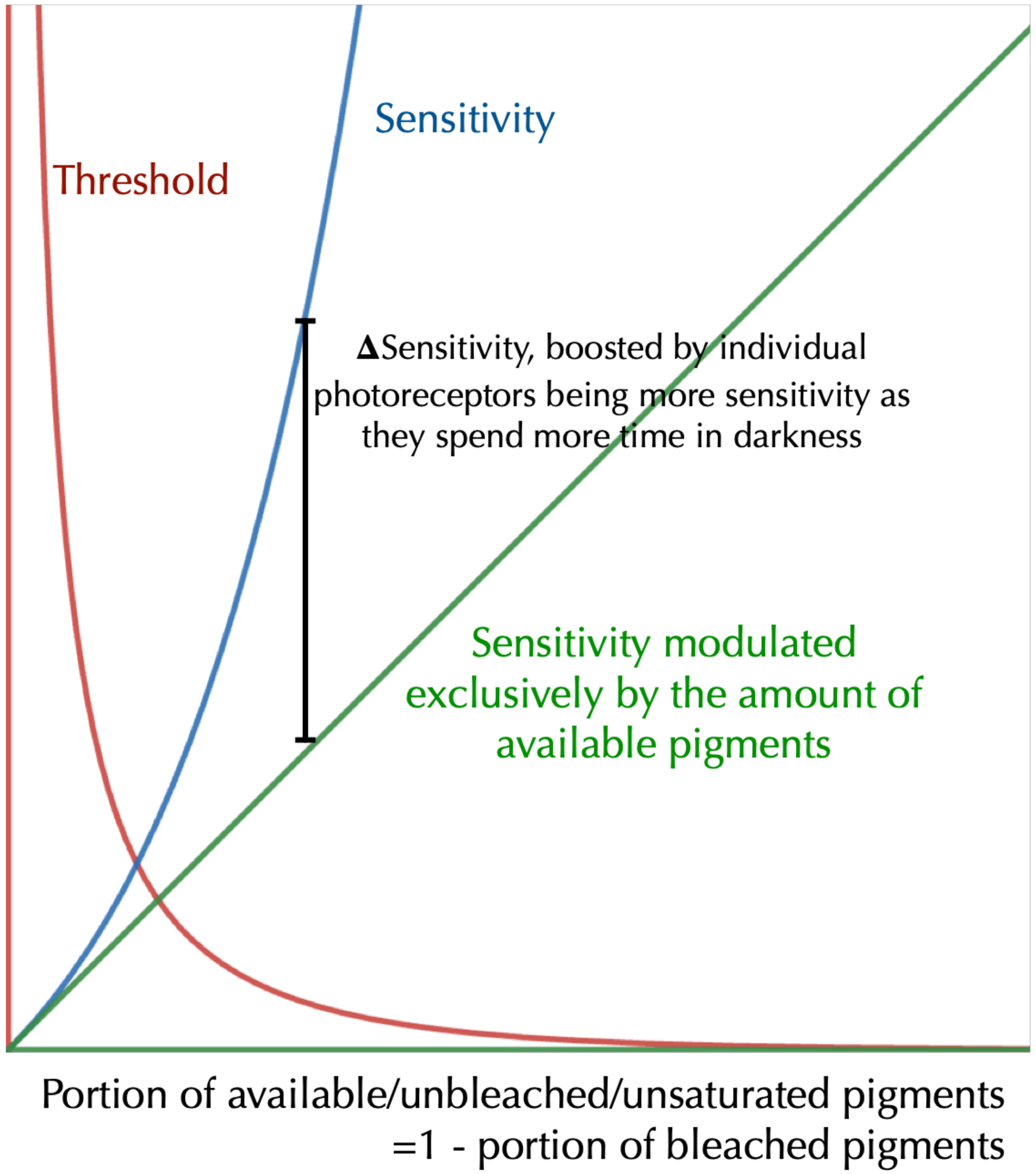
Pigment Regeneration

Bleach all pigments using intense light, then remove light, and measure % of pigments vs. time.
Pigment regeneration in cones is faster than in rods — half time 3X faster (ignore left y-axes).





Sensitivity Recovery Rate > Pigment Regeneration Rate



- Threshold decays exponentially as the number of available pigments increases.
- So the pigment sensitivity recovery rate is higher than the pigment regeneration rate.
- So the photoreceptor itself must also become more sensitive over time.
  - "Free opsin" (Lamb & Pugh 2004; Lamb & Pugh 2006, Proctor Lecture)

Illustration based on raw data in Cornsweet, T.N., Visual Perception. 1970

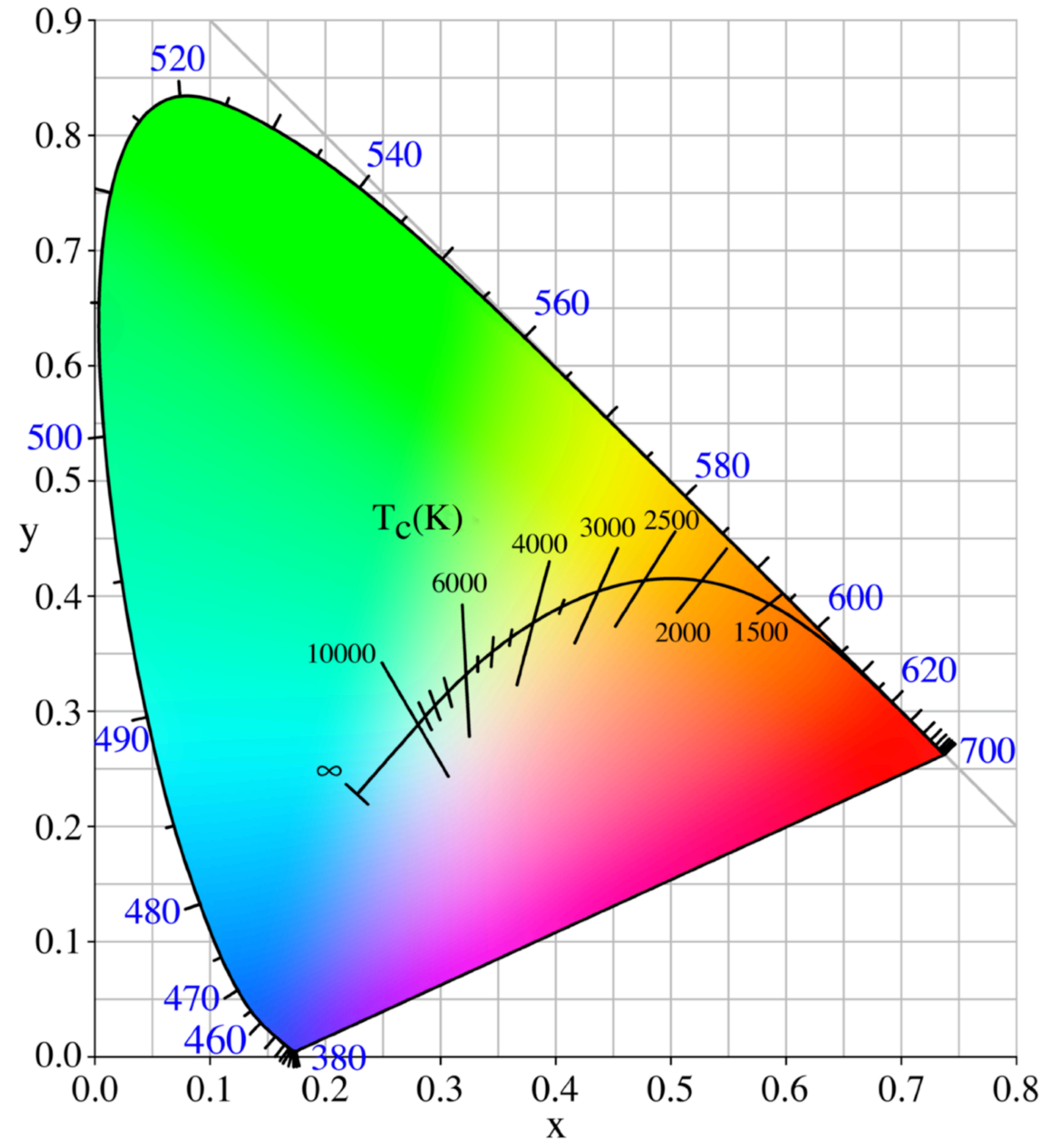
Chromatic Adaptation


It doesn't look white as we are looking at the photo now, but would look white to our eyes when we were sitting in front of it at the moment.
Does it look white?
Should it look white?
NICK MORRIS

"Color Constancy"

Clear blue poleward sky Overcast daylight sky

Objective colors under different illuminants are very different, but our subjective color perception is not nearly that different.



https://www.dpmag.com/how-to/shooting/what-is-white-balance-on-your-camera/

"Color Constancy"

The objective color of the scene. Color is reddish because the illuminant is ~tungsten.

The color you actually see when in the scene.

https://photovideocreative.com/en/have-color-neutral-photo-with-smartphone-neither-too-bluish-nor-too-orange/

Color Constancy and Chromatic Adaption

Human visual system adjusts to changes in illumination to preserve the relatively constant appearance of “**white**”.

Informally, a white paper is seen as white under many light sources. But different light sources actually have very different colors.

Appearances of other colors adapt too, but don’t adapt fully.

- Why? Evolution.

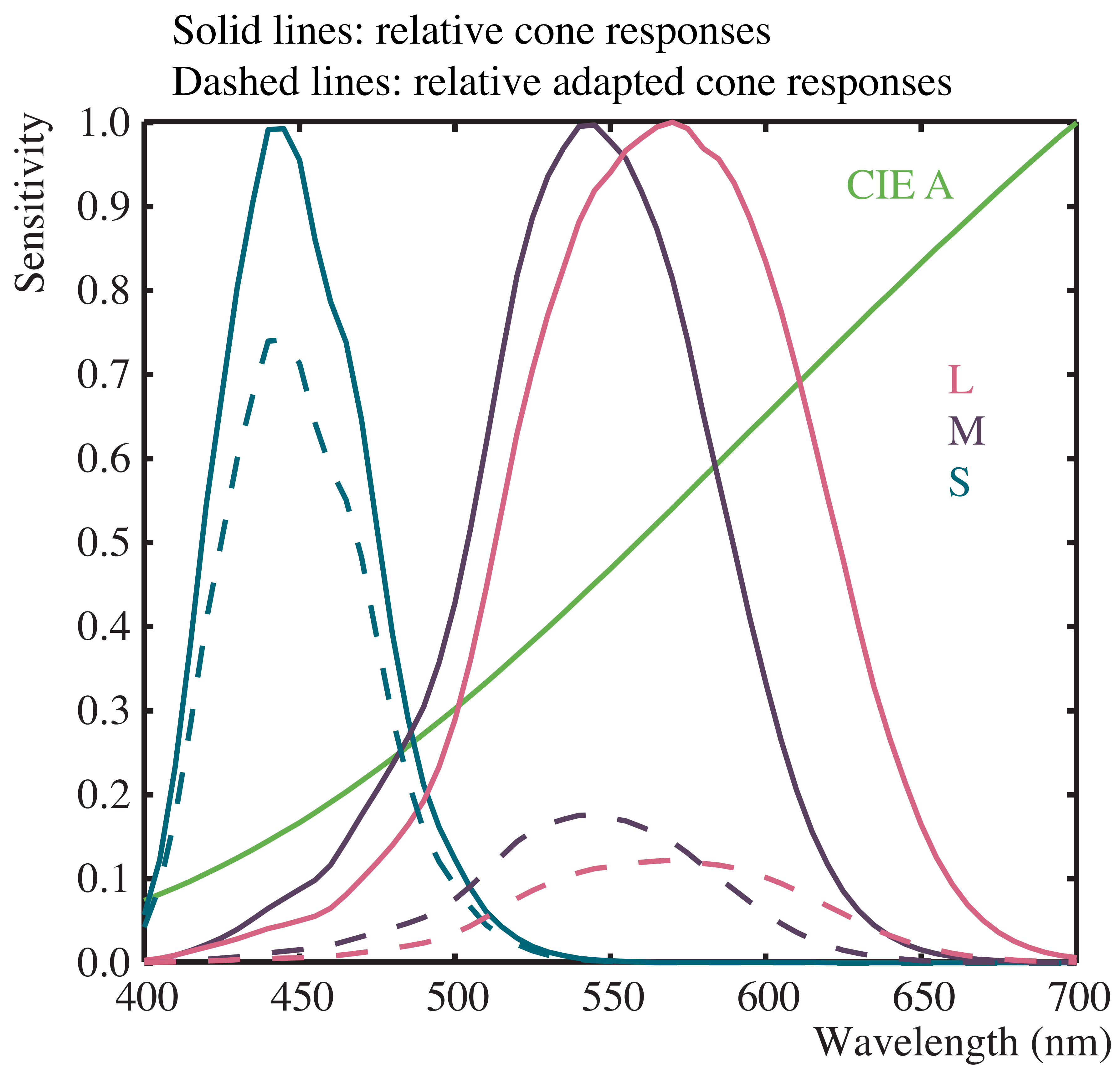
https://www.cg.tuwien.ac.at/research/publications/2009/wilkie-2009-cc/

Von Kries Chromatic Adaption Model

Hypothesis: The **cone responses** adapt to the illuminant. Cones become more/less sensitive depending on the illuminant.

- Each cone adapts independently.
- Each cone's "adaption factor" is inversely proportional to the cone's responses of the illuminant itself.

$$\begin{bmatrix} L_a \\ M_a \\ S_a \end{bmatrix} = \begin{bmatrix} \frac{1}{L_w},0,0 \\ 0,\frac{1}{M_w},0 \\ 0,0,\frac{1}{S_w} \end{bmatrix} \times \begin{bmatrix} L \\ M \\ S \end{bmatrix}, \quad where \begin{bmatrix} L_w \\ M_w \\ S_w \end{bmatrix} = \begin{bmatrix} \int \Phi(\lambda)L(\lambda)d\lambda \\ \int \Phi(\lambda)M(\lambda)d\lambda \\ \int \Phi(\lambda)S(\lambda)d\lambda \end{bmatrix}$$



Von Kries Chromatic Adaption Model

Neutral points all look as the same color under different illuminants.

- Neural points: points whose spectral reflectance is 1 everywhere. Informally we call it the **white** point.
- The color of a neural point is the color of the illuminant **without** illumination.
- So adaptation **discounts** the illuminant.

$$\begin{bmatrix} \frac{1}{L_{w1}},0,0 \\ 0,\frac{1}{M_{w1}},0 \\ 0,0,\frac{1}{S_{w1}} \end{bmatrix} \times \begin{bmatrix} L_{w1} \\ M_{w1} \\ S_{w1} \end{bmatrix} = \begin{bmatrix} \frac{1}{L_{w2}},0,0 \\ 0,\frac{1}{M_{w2}},0 \\ 0,0,\frac{1}{S_{w2}} \end{bmatrix} \times \begin{bmatrix} L_{w2} \\ M_{w2} \\ S_{w2} \end{bmatrix}$$

Unadapted responses of **neutral point** under the first illuminant

Unadapted responses of **neutral point** under the second illuminant

White Balance, a.k.a., Camera Chromatic Adaptation

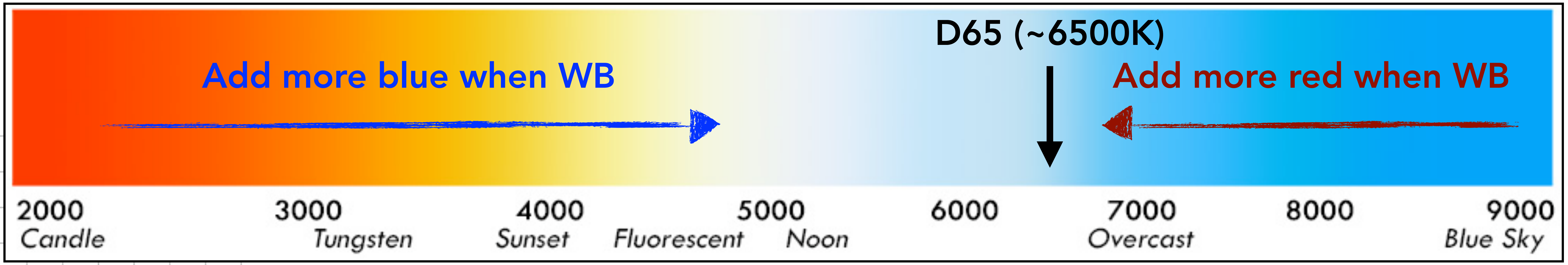
Human evolved over millions of years to learn to adapt to illuminants. But cameras don’t have this luxury — camera SSFs are fixed once fabricated.

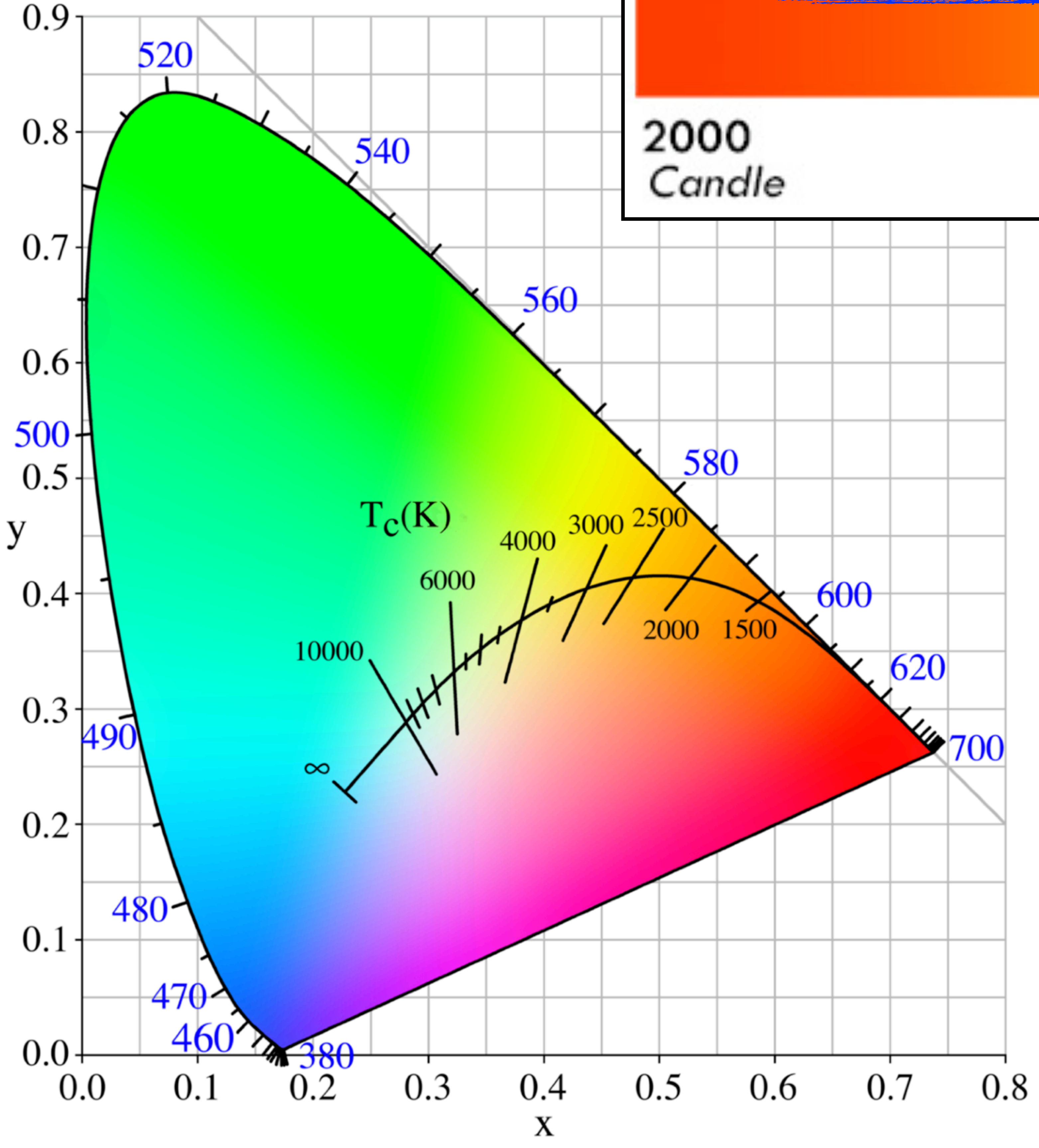
Goal: adapt colors so that the resultant image ***appears*** as the photographers “remember” based upon their adaptation state.

Photo without AWB

Photo with AWB

White Balance and Color Temperature





If a photo it assumed to be viewed under daylight (~D65, 6500K), AWB forces the white object in the photo to be D65 (sRGB reference white, blue-ish).

If the capture illumination is warmer (cooler), WB adds blue (red) to the scene. Some cameras allow you to explicitly set the temperature of the illumination for WB.

White Balance in Cameras

Read: http://yuhaozhu.com/blog/chromatic-adaptation.html

Linear sRGB color

Chromatic adaptation from capturing illuminant to viewing illuminant

Raw RGB in camera color space

$$\begin{bmatrix} SR \\ SG \\ SB \end{bmatrix} = T^{-1}_{srgb2xyz} \times T^{-1}_{xyz2lms} \times \begin{bmatrix} \frac{L_{w2}}{L_{w1}},0,0 \\ 0,\frac{M_{w2}}{M_{w1}},0 \\ 0,0,\frac{S_{w2}}{S_{w1}} \end{bmatrix} \times T_{xyz2lms} \times T_{cam2xyz} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Color correction matrix

Ideal vs. Practical White Balance

Ideal white balance is easy if we know:

- the illuminant of the capturing scene.
- the illuminant of the viewing scene.

If so, we can simply calculate the scaling factors of the LMS cone responses.

- Remember, RGB/XYZ is just one linear transformation away from LMS. So knowing how to scale LMS basically means we know how to scale RGB values too.

In reality: capturing illuminant is unknown.

The real work of auto white balance is to **estimate the capturing illuminant**.

(Semi-)Auto White Balance

How to know where a neutral point is (i.e., which pixel ***should*** look white under the capturing illuminant)?

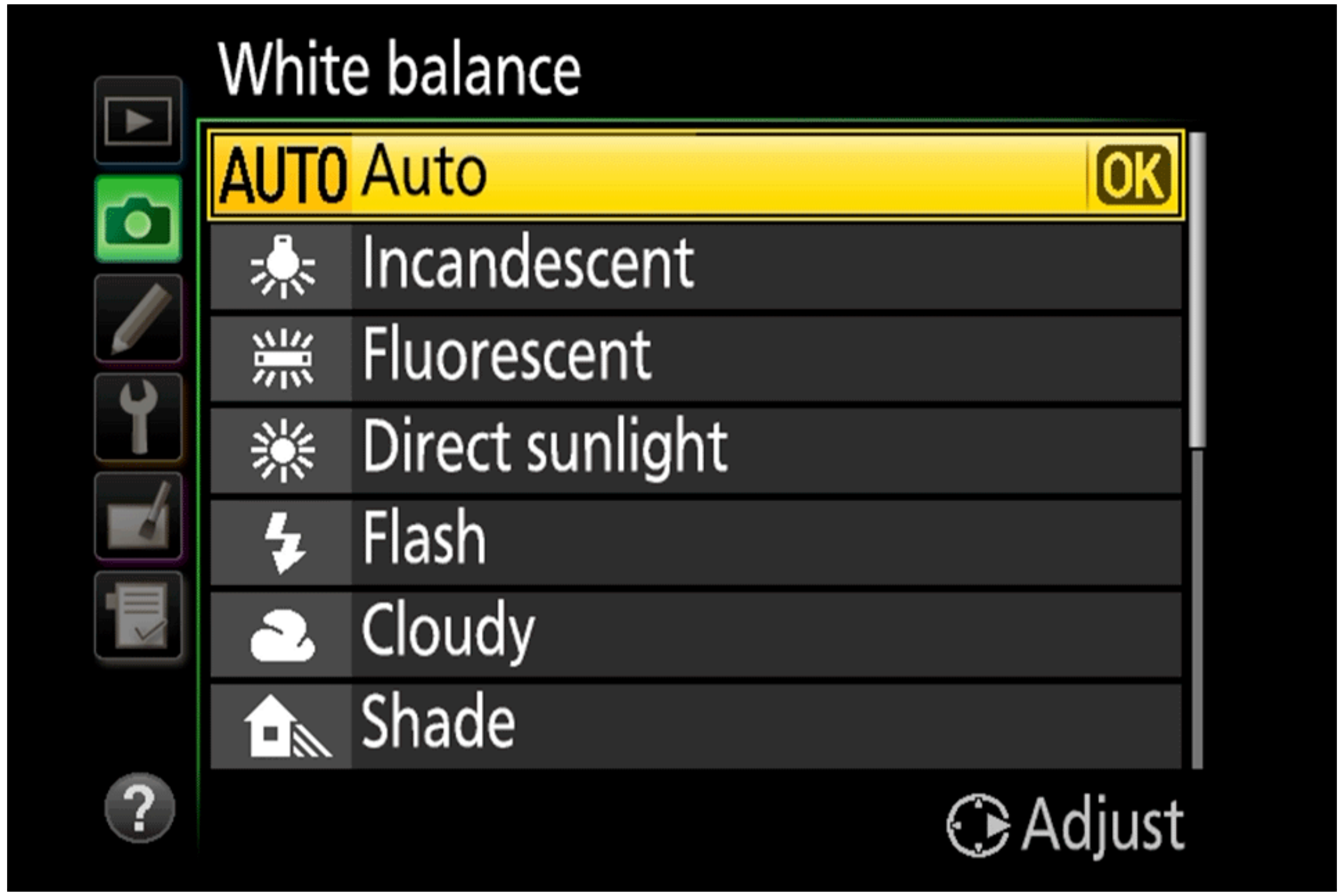
Pre-made reference white card

Can be used as a neutral point (lucky!)

https://www.vortexmediastore.com/pages/warmcards-white-balance-system https://photovideocreative.com/en/have-color-neutral-photo-with-smartphone-neither-too-bluish-nor-too-orange/

(Semi-)Auto White Balance

If a white point is unavailable, specify the capture illuminant and use a pre-calculated adaptation matrix, which is calculated offline from known illuminants.



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https://photovideocreative.com/en/have-color-neutral-photo-with-smartphone-neither-too-bluish-nor-too-orange/
https://photographylife.com/what-is-white-balance-in-photography

Illuminant Estimation by AWB

Many heuristics:

- Assume that the average color of all pixels in an image is gray (e.g., [128, 128, 128] in sRGB) and scale all pixels accordingly. Fails when the scene is colorful (close-up flower).
- Assume that the brightest pixel is white. Fails quite often (night scene with traffic lights).
- Other techniques try to guess the illumination: bright image is probably outdoor; dim images are probably indoor, etc.

Train deep learning models to predict capturing illuminant (example).

Visual Constancy

Color Constancy

Chromatic adaptation is purely a receptoral mechanism (sensitivity scaling)

Or visual system does more than sensitivity scaling to maintain a constant color perception.

The wildly accepted hypothesis is that our visual system first estimates the illuminant color from the world, and then discount the illuminant color to infer the **material** “color” (**reflectance** to be more rigorous), which is naturally invariant to illumination.

This is called color constancy.

Red Without Any Red Pixel

The cyan tint tricks your brain to think that the illuminant of the scene is cyan. So your brain subtracts cyan from colors it perceives.

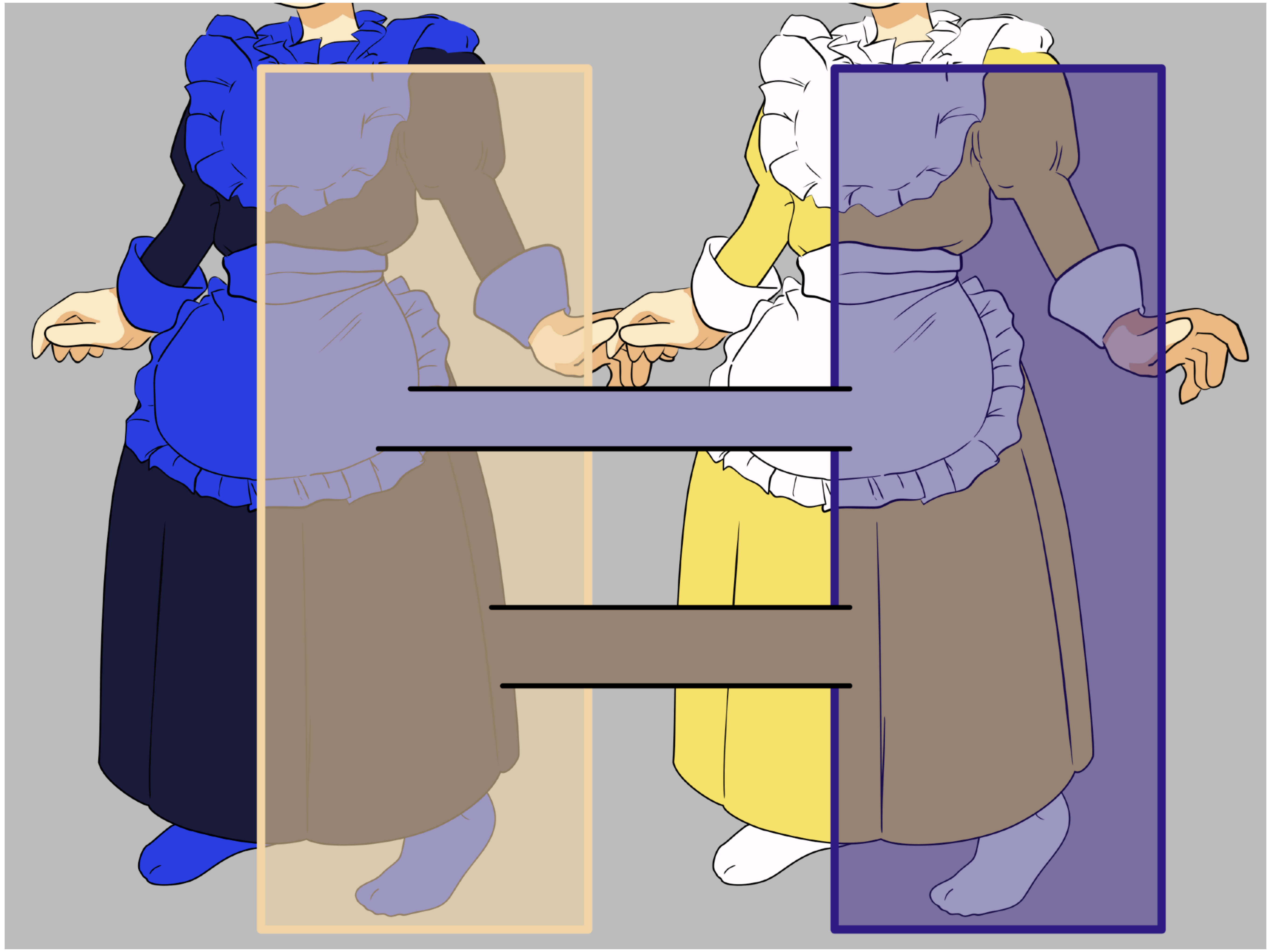
Subtracting cyan is like adding red (recall the RGB color cube), so the gray patches look red now.

https://www.vice.com/en/article/wnkq5n/this-picture-has-no-red-pixelsso-why-do-the-strawberries-still-look-red

Black and Blue or White and Gold?

https://en.wikipedia.org/wiki/The_dress

Black and Blue or White and Gold?

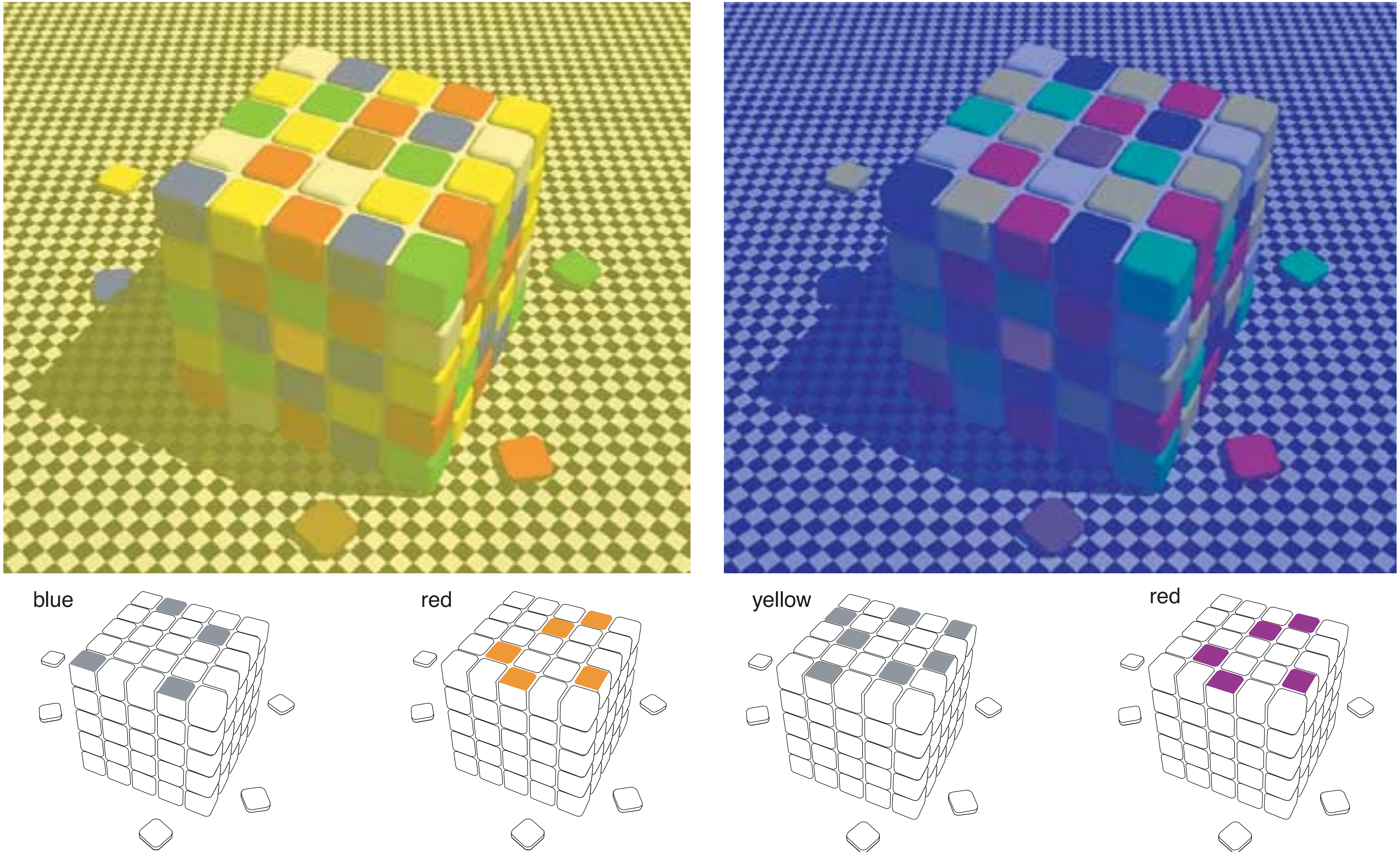


Left: if your visual system thinks the illuminant is yellow, it will subtract yellow (add blue) from the colors.

Right: if your visual system think the illuminant is blue, it will subtract blue (add yellow) from the colors.

Why different visual systems think differently is anyone's guess.

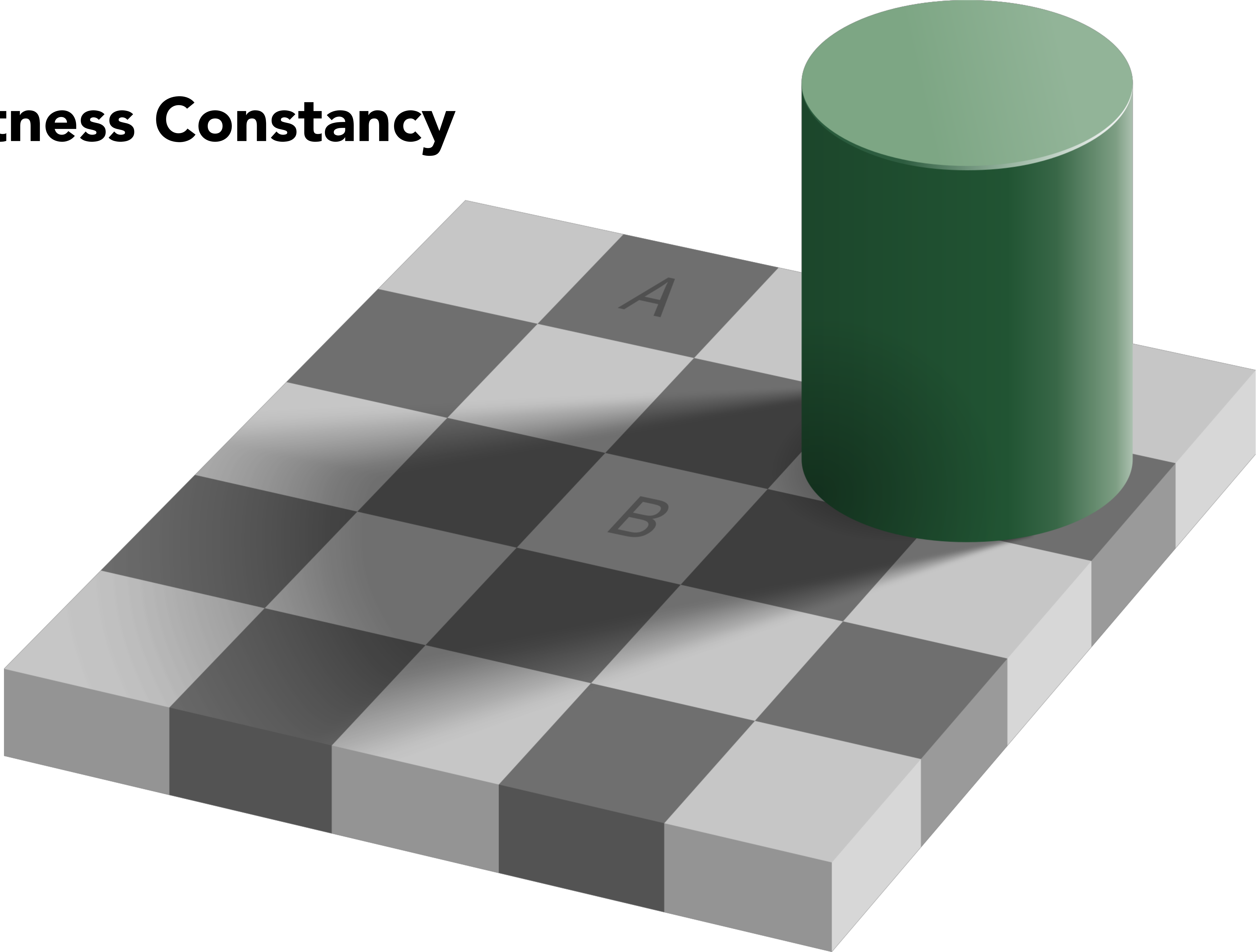
https://en.wikipedia.org/wiki/The_dress



Purves et al., 2002

Purves et al., 2002

Lightness Constancy



https://en.wikipedia.org/wiki/Checker_shadow_illusion#/media/File:Checker_shadow_illusion.svg

Lightness Constancy

https://en.wikipedia.org/wiki/Checker_shadow_illusion#/media/File:Checker_shadow_illusion.svg

Purves et al., 2002

Purves et al., 2002

Purves et al., 2002

Visual Constancy

Context and semantics are important

Retinal processing is likely incapable of extracting complex contextual and semantic information.

Visual constancy thus must involve higher-order, cognitive functions in the brain.

This also means memory, experience, etc. are important for our visual experience.