The Visual Perception of Images

- In order to understand "images" you must understand how humans perceive visual stimmulus.
- Objectives:
  - Understand contrast and how humans detect changes in images.
  - Understand photometric properties of the physical world.
  - Understand the percept of "color".
  - Learn how to use this understanding to design imaging systems.

Visual System Basics

- Retina - the "focal plane array" on the back surface of the eye the detects and measures light.
- Photoreceptors - the nerves in the retina that detect light.
- Fovea - a small region in the retina ($\approx 1^\circ$) with high spatial resolution.
- Blind spot - a small region in the retina where the optic nerve is located that has no photoreceptors.
- Rods - a type of photoreceptor that is used for achromatic vision at very low light levels (scotopic vision).
- Cones - a type of photoreceptor that is used for color vision at high light levels (phototopic vision).
- Long, medium, and short cones - the three specific types of codes used to produce color vision. This cones are sensitive to long (L or red) wavelengths, medium (M or green) wavelengths, and short (S or blue) wavelengths.

Luminance

- Luminance describes the "achromatic" component of an image.
- λ - wavelength of light
- Most light contains a spectrum of energy at different wavelengths. So that

$$\text{Energy between } \lambda_1 \text{ and } \lambda_2 = \int_{\lambda_1}^{\lambda_2} I(\lambda) d\lambda$$

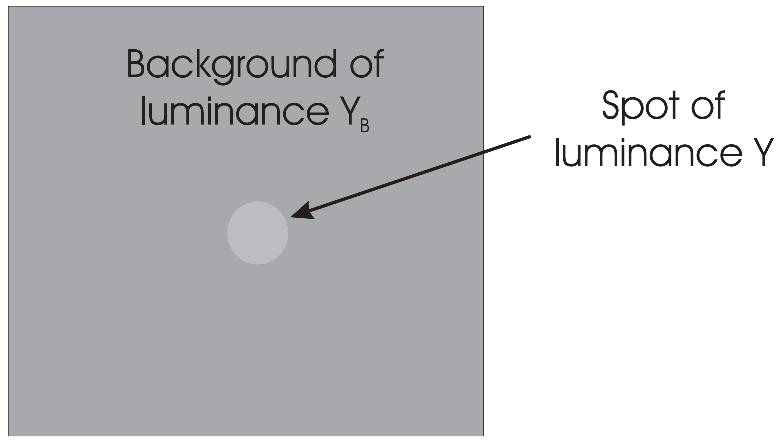
- Human visual system's (HVS) sensitivity is a function of wavelength. Most important region is from 400 nm to 700 nm.
- Informal definition: $L(\lambda)$ is the visual sensitivity as a function of wavelength.
- Luminance is defined as:

$$Y \triangleq \int_0^\infty I(\lambda) L(\lambda) d\lambda$$

- Note: Y is proportional to energy!!

A Simple Visual Stimulus

- A single uniform dot of luminance Y ($\approx 10°$) in a large uniform background of luminance Y_B.



  Question: How much difference is necessary for a “standard observer” to notice the difference between Y and Y_B?

- Definitions:
  - The just noticable difference (JND) is the difference that allows an observer to detect the center stimulus 50% of the time.
  - ΔY_{JND} is the difference in Y and Y_B required to achieve a just noticable difference.

The Problem with Linear Luminance

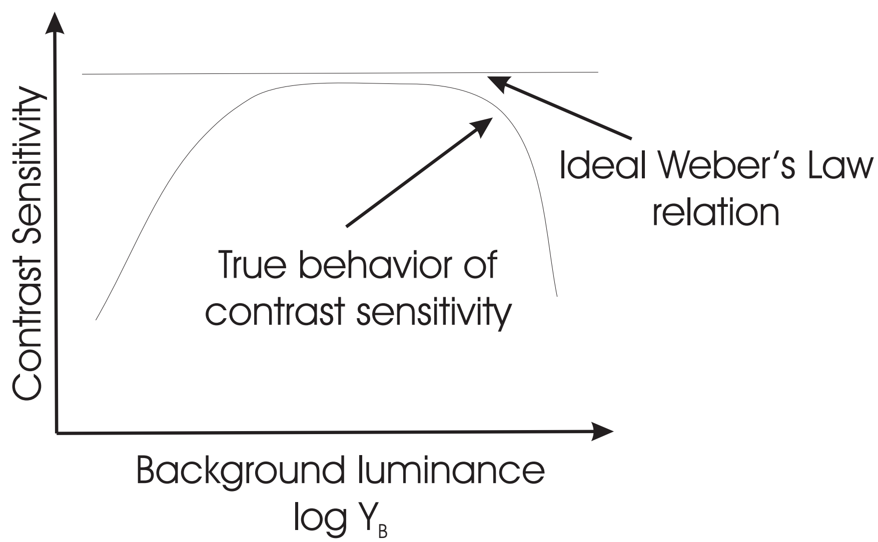
- Consider the following gedanken experiment:
  - **Experiment 1** - A visual experiment uses a background formed by a uniformly illuminated white board in an otherwise dark room. In this case, $Y_B = 1$ and $Y = 1.1$ achieves a JND. So, $\Delta Y_{JND} = 0.1$.
  - **Experiment 2** - A visual experiment uses a background formed by a uniformly illuminated white board in a bright outdoor environment. In this case, $Y_B = 1000$ and $Y = 1000.1$. Does $\Delta Y = 0.1$ still achieve a JND? **No!**
- Conclusion $\Rightarrow$ ΔY_{JND} is a strong function of the background luminance Y_B.

Weber's Law

- We need a quantity to measure JND changes in luminance which is independent (less dependent) on the background lumance Y_B.
- Definitions:
  - *Contrast* - $C \triangleq \dfrac{Y - Y_B}{Y_B} = \dfrac{\Delta Y}{Y_B}$
  - *JND Contrast* - $C_{JND} \triangleq \dfrac{\Delta Y_{JND}}{Y_B}$
  - *Contrast sensitivity* - $S \triangleq \dfrac{1}{C_{JND}}$
- Comments:
  - Contrast is the *relative* change in luminance.
  - A small value of C_{JND} means that you are very sensitive to changes in luminance.
  - A large value of C_{JND} means that you are very insensitive to changes in luminance.

Weber's Law

- Weber's Law: The contrast sensitivity is approximately independent of the background luminance.
  - Relative changes in luminance are important.
  - Weber's law tends to break down for very dark and very bright luminances.



- At very low lumanninces, detector noise, and ambient light tend to reduce sensitivity, so the stimulus appears "black".
- At very high luminances, the very bright background tends to saturate detector sensitivity, thereby reducing sensitivity by "blinding" the subject.
- We are most concerned with the low and midrange luminance levels.

Luminance Transformations

- Problem:
  - Unit changes in Luminance Y **do not** correspond to unit changes in visual sensitivity.
  - Is there a transformation of luminance $L = f(Y)$ which is more *visually uniform*? i.e. Fixed changes in L correspond to fixed changes in visual sensitivity?
- Partial answer:
  - Define $L = \log Y$ then

$$\begin{aligned}\Delta L &= L - L_B \\ &= \log Y - \log Y_B \\ &= \log\left(\frac{Y - Y_B}{Y_B} + 1\right)\end{aligned}$$

  - So changes in L are proportional to contrast.

$$\Delta L = \log\left(C + 1\right)$$

Log Luminance Transformations

$$L = \log Y$$

- Advantages:
  - Weber's Law says that fixed changes in L will correspond to equally visible changes in an image.
  - This makes L useful for problem such as image quantization, and compression.
- Problem:
  - $L = \log Y$ is not defined for $Y = 0$.
  - Webber's law is an approximation, particularly at low luminance levels were sensitivity is reduced.

Power Law Contrast

- Define $L_p = Y^p$ where typically $p < 1$.
- Then

$$\begin{aligned} \Delta L_p &= Y^p - Y_B^p \\ &= Y_B^p \left(\left(\frac{Y - Y_B}{Y_B} + 1 \right)^p - 1 \right) \end{aligned}$$

  Therefore, we have

$$\Delta L_p = Y_B^p \left((C+1)^p - 1 \right)$$

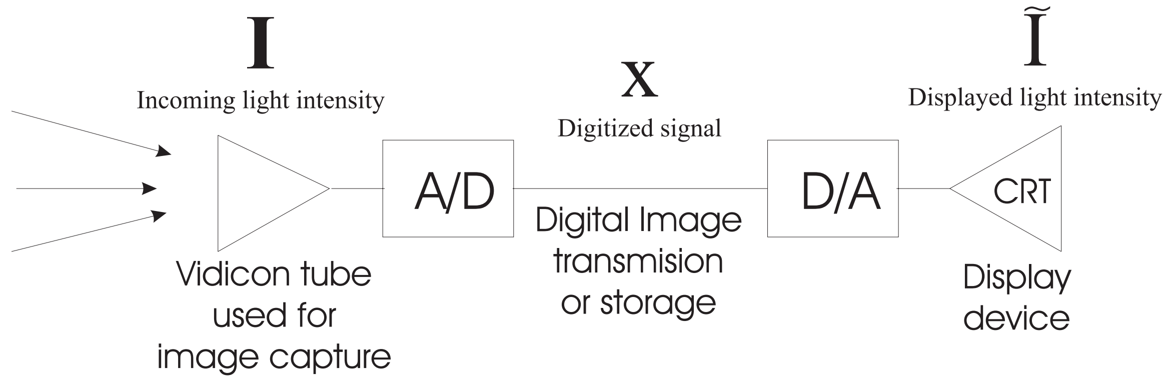
- Comments:
  - For fixed contrast, L_p increases with background luminance.
  - Increased $L_p \Rightarrow$ increased sensitivity with luminance.
  - As $p \to 0$, L_p behaves like L (i.e. $\lim_{p \to 0} Y_B^p = 1$).

Power Law Luminance Transformations

$$L_p = Y^p$$

- L_p is well defined for $Y = 0$.
- L_p models the reduced sensitivity at low luminance levels.
- $p = 1/3$ is known to fit empirical data well.
- $p = 1/2.2$ is more robust and is widely used in applications.
- We will see that $p = \frac{1}{\gamma}$ where γ is the parameter used in "gamma correction."
- Typical values of p:
  - NTSC video $p = 1/2.2$
  - sRGB color standard $p = 1/2.2$
  - Standard PC and Unix displays $p = 1/2.2$
  - MacIntosh computers $p = 1/1.8$
  - $L^*a^*b^*$ visually uniform color space $p = 1/3$

Input and Output Nonlinearities in Imaging Systems



- $x(m, n)$ generally takes values from 0 to 255
- Videcon tubes are (were) nonlinear with input/output relationship.

$$x = 255 \left(\frac{I}{I_{in}} \right)^{1/\gamma_i}$$

where I_{in} is the maximum input, and γ_i is a parameter of the input device.

- The cathode ray tube (CRT) has the inverse input/output relationship.

$$\tilde{I} = I_{out} \left(\frac{x}{255} \right)^{\gamma_o}$$

where I_{out} is the maximum output and γ_o is a parameter of the ouput device.

Gamma Correction

- The input/output relationship for this imaging system is then

$$\begin{aligned}
\tilde{I} &= I_{out} \left(\frac{x}{255} \right)^{\gamma_o} \\
&= I_{out} \left(\frac{255 \left(\frac{I}{I_{in}} \right)^{1/\gamma_i}}{255} \right)^{\gamma_o} \\
&= I_{out} \left(\frac{I}{I_{in}} \right)^{\gamma_o/\gamma_i}
\end{aligned}$$

  So we have that

$$\frac{\tilde{I}}{I_{out}} = \left(\frac{I}{I_{in}} \right)^{\gamma_o/\gamma_i}$$

- If $\gamma_i = \gamma_o$, then

$$\tilde{I} = \frac{I_{out}}{I_{in}} I$$

- Definition: The signal x is said to be *gamma corrected* because it is predistorted to display properly on the CRT.