Institute of Neuroinformatics
UNI/ETH Zurich

Biological and Computational Vision

Lecture 2
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www.ini.unizh.ch/~kiper/comp_vis/index.html
A section through the human retina

Receptors: rods and cones

Bipolar and Horizontal cells

Amacrine cells

Ganglion cells

Optic nerve

Dowling, 1987 (Fig 2.1)
Boycott and Dowling (1969)
Phototransduction in rods and cones

**Rods**: Vision in low light (e.g. night).

**Cones**: Vision in stronger light (e.g. day).

Dowling, 1987 (Fig 4.3b)
Distribution of rods and cones: a view from the side

Wandell, 1995 (Fig 3.1)
Response of a cone to light of two different wavelengths

Wandell, 1995 (Figs 4.15-4.16)
Principle of univariance
Light adaptation
Human light and dark adaptation

Light adaptation

Dark adaptation

Log threshold

Log background

Time (min)
The Jungfrau viewed from Wengen
We care for surface reflectance, not light intensity. Contrast is proportional to reflectance.

<table>
<thead>
<tr>
<th></th>
<th>Reflectance</th>
<th>Intensity $I$ at noon (1000000 W)</th>
<th>Intensity $I$ at dusk (1000 W)</th>
<th>Local contrast $c$ at noon (1000000 W)</th>
<th>Local contrast $c$ at dusk (1000 W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>90%</td>
<td>9000000 W</td>
<td>900 W</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Grass</td>
<td>40%</td>
<td>4000000 W</td>
<td>400 W</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Paper</td>
<td>80%</td>
<td>8000000 W</td>
<td>800 W</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ink</td>
<td>10%</td>
<td>1000000 W</td>
<td>100 W</td>
<td>-0.75</td>
<td>-0.75</td>
</tr>
<tr>
<td>Mean</td>
<td>40%</td>
<td>4000000 W</td>
<td>400 W</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Intensity $I$ is reflectance*illuminance.

*Local contrast is $c = (I-I_{mean})/I_{mean}$.*
Cone responses adapt to background illumination

Norman & Perlmann (1979)
Light adaptation is somewhat local in space
Ganglion cells
Basic retinal circuitry

- Receptor terminals (RT)
- Horizontal cells (H)
- Bipolar cells (B)
- Amacrine cells (A)
- Ganglion cells (G)
- Optic nerve
Concentric receptive fields
Ganglion cells adapt to the mean light intensity

Sakmann and Creutzfeldt (1969)
Ganglion cells have center-surround receptive fields

Dowling, 1987 (Fig 2.13)
Examples of responses of an ON-center cell

Enroth-Cugell and Robson (1984)
Examples of responses of an OFF-center cell

Enroth-Cugell and Robson (1984)
Center-surround receptive fields enhance edges
The linear model
A model of the ganglion cell receptive field

ON-center receptive field

“Difference of gaussians” model
\[ R(x,y) = \int\int F(u,v) I(x+u, y+v) \, dudv \]
Assumptions implicit in the last 3 slides

- Receptive fields are difference of gaussians
- Responses are a weighted average of the stimulus intensity, where the map of the weights is the receptive field.

Are these assumptions reasonable?
The second assumption is true if and only if the cell is a linear system.

Linear systems $L(x)$ obey

- homogeneity: $L(a \cdot x) = a \cdot L(x)$
- superposition: $L(x+y) = L(x) + L(y)$
Homogeneity

Original input

Intensity

0 1 2 3

Space

-5 0 5

Original input X 2

Output

Neural response

-1 0 1 2

Retinal space

-5 0 5

Output X 2

Neural response

-1 0 1 2

Retinal space

-5 0 5
Superposition

**Input 1**

![Graph showing the intensity distribution of Input 1 in space and retinal space.]

**Output 1**

![Graph showing the neural response for Output 1 in retinal space.]

**Input 2**

![Graph showing the intensity distribution of Input 2 in space and retinal space.]

**Output 2**

![Graph showing the neural response for Output 2 in retinal space.]

**Sum of inputs**

![Graph showing the intensity distribution of the sum of inputs in space and retinal space.]

**Sum of outputs**

![Graph showing the neural response for the sum of outputs in retinal space.]
Linearity is often checked by using sinusoidal stimuli, because for a linear system:

1) The responses to sinusoids are sinusoids.

2) The dependence of response on stimulus frequency can be predicted from the shape of the receptive field.

(so if any of these two are false, the system is not linear)
Responses of a linear system to sinusoids

- **Impulse Response:**
  - Input (Intensity): 1
  - Neural Response: Peaks

- **Low Frequency Sinusoid:**
  - Input (Intensity): Sine wave
  - Neural Response: Sine wave

- **Higher Frequency Sinusoid:**
  - Input (Intensity): Rapidly changing sine wave
  - Neural Response: Oscillating pattern

**Axes:***
- **Space:**
  - Scale: -5 to 5
- **Retinal Space:**
  - Scale: -5 to 5
A sinusoid in 2-D: a sinusoidal grating

Contrast = \( C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \)

\( I = I_{\text{av}} C \sin 2\pi FS \)
Predictions of the linear model with a ‘‘difference of gaussians’’ receptive field

Enroth-Cugell and Robson (1984)
Fitting the model to the data

Enroth-Cugell et al. (1983)
The fits are good: the responses to sinusoids are predictable by a linear model with a “difference of gaussians” receptive field.

Let’s try another test of linearity. If it succeeds as well, we’ll be happy with the model.
Making a square wave with sinusoids

Add 5 more odd harmonics up to $\frac{\sin(15\omega t)}{15}$

Add all higher odd harmonics

Barlow and Mollon, 1982 (Fig 1.2)
Square waves in 2-D
Responses of a ganglion cell to edges

Enroth-Cugell and Robson (1984)
Chevreuil illusion - Mach bands
Sensitivity for different spatial frequencies
Spatial frequency tuning of a ganglion cell

Enroth-Cugell et al. (1983)
Spatial frequency sensitivity curve of a whole brain

![Graph showing spatial frequency sensitivity curve with observations](image-url)
Contrast sensitivity varies with spatial frequency
One interpretation of the contrast sensitivity curve