SOME RELATIONS BETWEEN VISUAL PERCEPTION AND NON-LINEAR PHOTONIC STRUCTURES

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MAIN OBJECTIVE

To present a way to emulate some functions of the mammalian visual system and a model to analyze subjective sensations and visual illusions

TOPICS TO BE COVERED

1. Summary of Sensing in Living Bodies
2. Mammalian Visual System: Retina and Visual Cortex
3. Photonic devices with non linear behaviour
6. Conclusions
SOME PREVIOUS HISTORY
TO REMEMBER
MAXWELL Ecs: Radio, TV, Radar, ...


Photonics

Electronics

Optics

Biology

Electricity

Magnetism

Solid State

¿? (Neuronics?)

s. XIX

s. XX

s. XXI

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Possible ways for working

- Photonics as a tool to understand biology.

- Biology as a source of ideas for Photonics.

- Photonics as a source of concepts for Biology and vice versa.
LIVING BODIES AND ARTIFICIAL SYSTEMS
MAIN DIFFERENCE BETWEEN SENSING IN LIVING BODIES AND IN ARTIFICIAL SYSTEMS:

LIVING BODIES ARE ABLE TO INTERPRET STIMULI, THAT IS, ENVIRONMENTAL STIMULI AND THE RESPECTIVE RESPONSES OF SENSE ORGANS CORRESPOND TO STATEMENTS BY THE SUBJECT ABOUT HIS SENSATIONS AND PERCEPTIONS.
Objective sensations

Interaction with senses

Sensory stimuli

Appropriate receptors suprathreshold

Excitation in sensory nerves

Functioning brain centers

Subjective sensations

Rel. env.

Training

Sensory Impressions CNS

Perception

Memory

Prev. exp.

External Phenomena

Objective sensations

Subjective sensations
EXAMPLE

(according to P. MONDRIAN)
COUNTEREXAMPLE

(according to R. MAGRITTE)
Ceci n'est pas une pipe.
Mammalian Visual System: Retina and Visual Cortex

- Building blocks
- Building structures
- Signals involved
- Main characteristics
Building blocks:
Neurons and Receptors
Different neurons from the mammalian cortex
Different types of sensory receptor cells in vertebrates
Building structures: Circuits and Networks
The simplest types of microcircuits
Basic "circuits", corresponding to different cortex regions, are similar in outline and in several details.

**Common principles:**

In each region there is an initial stage of input processing, a second stage of intrinsic operations within the synaptic circuits of the region, and a final stage of output control.
CONVERGENCE AND DIVERGENCE

Once the superficial sensing units have received the external signal, a first processing step is carried out in a few cell layers. Usually, the number of sensing cells, in the first stratum, is much larger than the corresponding to neurons at successive layers.
Approaching to the mammalian retina: a model
Synaptic contacts in the vertebrate retina

Photoreceptors

Bipolar Cells

Horizontal Cells

Amacrine Cells

Ganglion Cells
The neural chain: (a) input part of the visual system, (b) convergence and divergence
Dowling’s model of the mammalian retina
Tools for modeling the mammalian retinal: non linear photonic devices
Semiconductor Electronic Devices

100 photons ($\lambda_0 = 1 \mu m$)

Basic configurations of FP laser diode amplifiers (a) transmission and (b) reflection.
Fabry-Perot Laser Diode Amplifiers

- They exhibit Optical Bistability (OB) under external signal injection.
- Dispersive Optical Bistability.
- Presence of Optical Gain.
- Low Input Power Requirements.
- Different operating Wavelengths.
- Easy to obtain.
Bistability in FPLDAs

**Reflection:** Anticlockwise, X- and clockwise bistable loops.

**Transmission:** Anticlockwise bistable loops.

Transmission: Anticlockwise bistable loops.

Reflection: Anticlockwise, X- and clockwise bistable loops.
### Individual Responses

#### Laser Parameter Values

<table>
<thead>
<tr>
<th>Laser1</th>
<th>Laser Parameter</th>
<th>Laser2</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>Cavity Length ($\mu$m)</td>
<td>400</td>
</tr>
<tr>
<td>0.3</td>
<td>Left/Right Facet Reflectivity</td>
<td>0.3</td>
</tr>
<tr>
<td>0.5</td>
<td>Confinement Factor</td>
<td>0.5</td>
</tr>
<tr>
<td>2.2 \cdot 10^{-16}</td>
<td>Linear Material Gain Coeff. (cm$^2$)</td>
<td>2.2 \cdot 10^{-16}</td>
</tr>
<tr>
<td>6.9</td>
<td>Linewidth Enhancement Factor</td>
<td>6.9</td>
</tr>
<tr>
<td>5000</td>
<td>Fixed Internal Loss (1/m)</td>
<td>5000</td>
</tr>
<tr>
<td>0.84</td>
<td>Bias/Threshold current</td>
<td>0.92</td>
</tr>
<tr>
<td>0.28 \cdot \pi</td>
<td>Initial frequency detuning</td>
<td>0.2125 \cdot \pi</td>
</tr>
</tbody>
</table>

#### Diagrams

- **Reflection**
  - $P_{\text{out}}$ ($\mu$W) vs. $P_{\text{in}}$ ($\mu$W)

- **Transmission**
  - $P_{\text{out}}$ ($\mu$W) vs. $P_{\text{in}}$ ($\mu$W)
Possible configurations for feedback in laser structures, (a) with transmitting signal, and (b) with reflecting signal from the first laser.
\[ I_{bias1} \quad I_{bias2} \]

\[ I_{1} + I_{2} \quad I_{\text{reflected}} \]

\[ g \]

Laser 1  \quad O_1  \quad \text{Laser 2}
Basic unit to configure the main architecture:
Optical Programmable Logic Cell (OPLC)
Block Diagram of a Q-device

Block Diagram of P-Device.

Logic Table for the OLG.

\[
\begin{array}{c|c|c|c}
\hline
O_1 & h_0 & h_1 & h_2 \\
\hline
\end{array}
\]

\[
\begin{array}{c|c|c|c}
O_1 & AND & OR & ON \\
\hline
\end{array}
\]

\[
\begin{array}{c|c|c|c|c|c}
\hline
g_0 & g_1 & g_2 & g_3 & g_4 \\
\hline
O_2 & OR & NAND & NOR & AND & OR \\
\hline
\end{array}
\]
Block Diagram a Q-device

\[ I_1 \rightarrow h \rightarrow Q \rightarrow O_1 \rightarrow I_2 \]

Logic Table for the OLG.

<table>
<thead>
<tr>
<th>h_0</th>
<th>h_1</th>
<th>h_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>O_1</td>
<td>AND</td>
<td>OR</td>
</tr>
</tbody>
</table>

**Transfer characteristic** \( P_{\text{out}}(P_{\text{in}}) \)

**Fabry-Perot Laser Diode**

**DFB Laser Diode**

![Graph of transfer characteristic](image)
Block Diagram of P-Device.

FP-LD configuration

Logic table for OLG.

<table>
<thead>
<tr>
<th>g0</th>
<th>g1</th>
<th>g2</th>
<th>g3</th>
<th>g4</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2</td>
<td>OR</td>
<td>NAND</td>
<td>NOR</td>
<td>AND</td>
</tr>
</tbody>
</table>

Laser 1

Optical Input
(I1 + I2 + g)

Laser 2

Optical Output

\[ P_{out\_laser2} (\mu W) \]

\[ P_{in\_laser1} (\mu W) \]
Schematic of the model simulated by VPI_ComponentMaker th software tool for Q-device
Schematic of the model simulated by VPI_ComponentMaker software tool for P-device
INSTABILITIES:

\[ \tau_e \]

\[ \tau_i \]

OB CONFIGURATION
Characteristics of the output signals, according to the delay times.

<table>
<thead>
<tr>
<th>$t_p$</th>
<th>$\tau_e$</th>
<th>$\tau_i$</th>
<th>$\tau_i / \tau_e$</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>200</td>
<td>2</td>
<td>0.01</td>
<td>280</td>
</tr>
<tr>
<td>14</td>
<td>200</td>
<td>4</td>
<td>0.02</td>
<td>140</td>
</tr>
<tr>
<td>14</td>
<td>200</td>
<td>12</td>
<td>0.06</td>
<td>70</td>
</tr>
</tbody>
</table>

$\tau_e = \text{external delay time}$  
$\tau_i = \text{internal delay time}$
Output signal with a period of 280.

Output signal with a period of 140.

Output signal with a period of 70.
APPLICATION TO THE MAMMALIAN RETINA
Information about the intensity of each one of the scene details are transferred from the third retina layer to following levels after a conversion from intensity level to frequency. Lower intensities correspond with lower frequencies.
FIRST STEPS TOWARDS THE DETECTION OF SOME GENERAL PROPERTIES OF IMAGES
XOR

Control signal

Input signals

Output signals

Control signal
(a) Symmetry: A logic "0" is always obtained at the 6th layer

(b) Asymmetry: A logic "1" is always obtained at the 6th layer
Other Asymmetries

1 1 0 0 0 0 1 0 0 0 0 0 0 1 1 1 0 0 0 0 1 1 1 0 0 0 1 1 1 1 0 1 1 0 1 1 1 0 1 1 1 0 1 0 1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

A logic "1" is obtained at the center of an even row
Approaching to the visual cortex: signals processing and sensing
Brodmann's cytoarchitectural map of the human cerebral cortex
Information is always transferred in a parallel way. As a consequence, the number of physical paths is very high.
(2) Each small piece of information goes to a particular area in the cortex where is analyzed with respect to other inputs and memories.
Behavior of the living beings sensors

Response (frequency of action potentials)

Stimulus intensity

S (Stimulus intensity at receptor)

Receptor potential

threshold

Action potentials

Depolarization

time

time

time

Stimulus intensity

Response

Behavior of the living beings sensors
THE CASE OF THE VISUAL CORTEX
Highly schematic view of the projections from the retina to various visual areas of the cerebral cortex.
PROJECTIONS FROM THE RETINA TO THE OCULAR DOMINANCE COLUMNS
Information about different line orientations is transferred to selected areas at the visual cortex. These areas become excited by this information and living beings get a stimulus concerning that orientation in the visual scene.
Each particular orientation, or each particular shape, goes to a precise area in the V1 area of the visual cortex. There is a certain type of “mapping” from the scene to the cortex: distributed measurements are transferred through a “multiplexed” system.
Visual cortex, at area V1, gets a "virtual image" of the real image appearing in the scene as "seen" by the living beings.
Maps of the Visual Field onto Area V1

When a pattern of flickering lights is shown in the visual field of a macaque, a map of striate cortex is revealed by 2-DG uptake.
Information about different visual information is transferred to selected areas at the visual cortex. These areas become excited by this information and living beings get a stimulus concerning that information in the visual scene.
Responses to faces in inferotemporal cortex
(a) The location of area IT in the inferior temporal lobe (b) Responses of a face cell. The histograms show the response of a neuron (spikes/sec) in monkey inferotemporal cortex to different views of a monkey's head. The horizontal bar under each histogram indicates when the stimulus was present.
Although different types of information processing appear in the retina and visual cortex this processing is the result of interchange of information among neurons in the same level. **No feedback processes** appears in the neural network.
Any biological information processing is performed by non linear effects.
The number of levels needed to go from receptor neurons in the retina to V1 layer in the cortex is lower than 15.
A possible way to implement a similar philosophy is with **WDM techniques**: a large number of information channels may go through the same physical path.
Photonic processing subsystem based on visual cortex architecture
Processing of data

- Extension of lines in each direction
- Distance between lines in each direction
- Main direction in object
- Analysis of orientations in each area
- Image details: orientations appearing in the subject
- Image division in small areas

Image to be analyzed
FEATURE INTEGRATION FRAMEWORK

Integrated Map

Attention window

Color

Size

Orientation

Stimulus
INFORMATION CORRESPONDING TO DIRECTION CHARACTERISTICS

DISTRIBUTION SYSTEM (1)

VS

HS

DS

VS

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Example: transferring information from a 2-D image
DATA OBTAINED FROM LETTER “F” (JUST 2 DIRECTIONS)
DATA OBTAINED FROM
LETTER "H" (JUST 3
DIRECTIONS)
GENERAL STRUCTURE OF THE SYSTEM
Sampling
(4 directions)

Redistribution (4 directions)

Threshold
(1.5 p.e.)
SOME CONCLUSIONS

- Once the signal is perceived, similar circuits are in charge of the information processing, without taking into account the type of sensed signal.
- Information is always analyzed, just by hardware tools, as a function of the resulting frequency and no of its absolute value.
- Transferring of information is by parallel paths.
- Signals travel along long paths without change in their properties.
- Each type of information is processed at specific places in the cortex.
SOME POINTS TO BE CONSIDERED IN THE NEXT FUTURE:
At a high level, in the human brain, many cells cooperate in a purposeful manner to produce perception, thinking, speech, writing and many other phenomena. In all these cases, new qualities emerge at a macroscopic level, qualities that are absent at the microscopic level of the individual.
ON SUBJECTIVE IMPRESSIONS OR HOW TO PUT NUMBERS TO VISUAL ILLUSIONS
Müller-Lyer Illusion

Effect of angles on the length sensation
Hering’s Illusion

Zöllner Illusion
Extended Parallelism Illusion from the Zöllner effect

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Analysis of the Müller-Lyer Illusion
MÜLLER-LYER ILLUSION

\[ \Lambda = \frac{\sum_{1}^{n} \sigma_{B_n} \lambda_{n}^2}{\sum_{1}^{n} \sigma_{B_n} \lambda_{n}} \]

\( \Lambda \): subjective length  
\( n \): total number of excited columns  
\( \sigma_{B_n} \): total number of bits obtained from the nth column  
\( \lambda_{n} \): distance of column \( n \) to the centre of image in column units
\[ \Lambda = \frac{\sum_{1}^{n} \sigma_{B_n} \lambda_{2_n}}{\sum_{1}^{n} \sigma_{B_n} \lambda_{n}} \]

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col. num.</td>
<td>1 2 3 4</td>
<td>1 2 3 4 5 6</td>
</tr>
<tr>
<td>Bits</td>
<td>3 1 1 3</td>
<td>2 1 1 1 1 2</td>
</tr>
<tr>
<td>Tot. Bits</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Tot. Col.</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Length</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda )</td>
<td>( 2 \times \frac{13}{7} = 3.72 )</td>
<td>( 2 \times \frac{23}{9} = 5.1 )</td>
</tr>
</tbody>
</table>

\[(3.4+1.1+1.1+3.4)/(3.2+1.1+1.1+3.2)\]
ANALYSIS OF THE
ZÖLLNER ILLUSION
ANALYSIS OF PARALLELISM

Main factor: symmetry with respect to the parallel line located at the middle between the two parallel lines.

Main influences: location and angles - "weight" - of the intersecting lines.
EXPERIMENTAL MEASUREMENT OF THE MÜLLER-LYER ILLUSION
(Black and blue curves correspond to two different conditions of the experiment)(from R. Gregory. “Eye and Brain”. 1990)
MAIN RULES:

1. Take the principal symmetry axis
2. Divide each region in “sensory zones”
3. Analyze each zone with respect to the principal axis
4. Construct the “sensory” matrix with elements from each zone
5. Apply the main symmetry operation to overlap different motives
6. Normalize
7. Reduce to a 1 x 1 matrix
Symmetry operations in two sets of parallel lines with small crossing lines

\[ C_2 \]
\[ \alpha \]
\[ T \]
\[ D_2 \]

\( C_2 = \text{twofold axis} \quad T = \text{translation} \quad D_2 = \text{inversion} \)
PROPOSED FORMULAE:

\[
\sigma_{\alpha k} = \left\{ \sum_{i=1}^{n} \omega_i \delta_i \right\}_{\alpha k} + S \left\{ \sum_{j=1}^{n} \omega_j \delta_j \right\}_{\alpha k}
\]

\( \omega \) = line “weight” \quad \( \delta \) = distance to the central line \quad \( S \) = symmetry operation

\( i, j \) = each one of the lines \quad \( \alpha, k \) = each one of the unit intervals

“sensory” matrix: \( \sigma_\alpha = [\sigma_{\alpha 1}, \sigma_{\alpha 2}, \ldots, \sigma_{\alpha k}, \ldots] \)

“reference” matrix: \( \wp_\alpha = [\wp_{\alpha 1}, \wp_{\alpha 2}, \ldots, \wp_{\alpha k}, \ldots] \)

“normalized” matrix: \( \pi_\alpha = [\sigma_{\alpha 1}/\wp_{\alpha 1}, \sigma_{\alpha 2}/\wp_{\alpha 2}, \ldots, \sigma_{\alpha k}/\wp_{\alpha k}, \ldots] \)

“reduced” matrix: \( \pi_\beta = [\pi_{\alpha 1}-\pi_{\alpha 2}, \ldots, \pi_{\alpha k}-\pi_{\alpha (k+1)}, \ldots] \)

If \( \Pi_\gamma = [0,0,\ldots] \) parallelism is “seen”

If \( \Pi_\gamma \neq [0,0,\ldots] \) parallelism is not “seen”

\{ \wp \) is a similar effect corresponding to the parallel lines\}
Subjective parallelism: \( \Pi \)

\[ \sigma_1 : (6x1+9x0.5) ; (6x1+7x0.5) ; (6x1+5x0.5) ; (6x1+3x0.5) \]

\[ \sigma_2 : (6x1+9x0.5) ; (6x1+7x0.5) ; (6x1+5x0.5) ; (6x1+3x0.5) \]

\[ \sigma_T \Rightarrow \sigma_1 + C_2 \sigma_2 \Rightarrow [10.5+10.5; 9.5+9.5; 8.5+8.5; 7.5+7.5] \]

\[ \begin{bmatrix} 21 & 19 & 17 & 15 \end{bmatrix} \]

\[ \varphi_T \Rightarrow \varphi_1 + C_2 \varphi_2 \Rightarrow [6+6; 6+6; 6+6; 6+6] \]

\[ \begin{bmatrix} 12 & 12 & 12 & 12 \end{bmatrix} \]

\[ \pi_i = (\varphi_T/\sigma_T)_i \Rightarrow [0.57 \ 0.63 \ 0.70 \ 0.8] \]

\[ \begin{align*}
\pi_l &= \pi_i - \pi_{i-1} : 0.06 & 0.07 & 0.1 \\
\pi_m &= \pi_l - \pi_{l-1} : 0.01 & 0.03 \\
\pi_n &= \pi_m - \pi_{m-1} : 0.02 
\end{align*} \]
$\sigma_1$: $(6x1+9x0.5); (6x1+7x0.5); (6x1+5x0.5); (6x1+3x0.5)$

$\sigma_2$: $(6x1+3x0.5); (6x1+5x0.5); (6x1+7x0.5); (6x1+9x0.5)$

$\sigma_T \Rightarrow \sigma_1 + C_2 \sigma_2: 10.5+7.5; 9.5+8.5; 8.5+9.5; 7.5+10.5$

$\varphi_T \Rightarrow \varphi_1 + C_2 \varphi_2: 6+6 ; 6+6 ; 6+6 ; 6+6$

$\pi_i = (\varphi_T / \sigma_T)_i :$ 0.67  0.67  0.67  0.67

$\pi_i = \pi_i - \pi_{i-1} :$  0.0  0.0  0.0

$\pi_m = \pi_i - \pi_{i-1} :$  0.0  0.0

$\pi_n = \pi_m - \pi_{m-1} :$  0.00  $\Rightarrow \Pi$
Analysis of the Hering and Wundt Illusions
(affected by the corresponding weight)
• A. González-Marcos and J.A. Martín-Pereda, “Method to analyze the influence of hysteresis in optical arithmetic units”. *Optical Engineering*, **40**, 2371-2385 (2001)
"Look, what thy memory cannot contain
Commit to these waste blanks, and thou shall find
Those children nursed, delivered from thy brain
To take a new acquaintance from thy mind"

(W. Shakespeare)