Building and Interpreting Populations of Model Visual Cortical Neurons

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Overview

- Visual cortical processing
  - Multidimensional selectivity

- Orientation Selectivity
  - What is it?
  - How do we implement it?
    - AER Multi-chip Architecture
    - DSP/FPGA Architecture

- Joint Orientation/Disparity Selectivity
  - Disparity energy model: position versus phase shifts
  - Population responses versus tuning curves
  - Bigger is not necessarily better
Cortical Visual Processing

From E. R. Kandel et. al., *Principles of Neural Science*

V1, primary visual cortex, or striate cortex

Retina
Level of Abstraction: Minicolumn

- “the effective unit of operation … is not the single neuron and its axon, but groups of cells with similar functional properties and anatomical connections.”

- “The basic unit of the mature neocortex is the minicolumn, a narrow chain of neurons extending vertically across the cellular layers II–VI, perpendicular to the pial surface (Mountcastle, 1978). Each minicolumn in primates contains ~80–100 neurons, except for the striate cortex where the number is ~2.5 times larger.”

Multidimensional selectivity

- Position
- Spatial frequency (size)
- Temporal frequency (change)
- Color
- Orientation
- Binocular Disparity (depth)
- Direction/speed of motion
- Curvature
Examples

input

Orientation.avi

input

Motion.avi
Why multidimensional selectivity?

- Measured in cortex
- Important perceptually
Improvement over isolated cues

- Motion and stereo
- Motion only
- Stereo only
Conclusion

- V1 reformats the visual data so that it is easier to interpret
  - I/O ratio for retina: 100/1 (compression)
  - I/O ratio V1: input:output ratio ~ 1:50 (expansion!)

- A neuromorphic systems for visual perception should simultaneously integrate information from all cues (orientation, disparity, motion) at a very early stage.
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Orientation Selectivity in V1


One area of visual field

180 deg

Track distance (millimeters)

Orientation (degrees)

1 millimeter
Orientation Map in V1
Model of Cortical Simple Cells

- Linear filtering to establish selectivity
- Half-wave rectification
- Squaring
- Normalization

```
input image → linear filtering → half-wave rectification → squaring → Normalization
```

“half squaring”
Gabor Receptive Field (RF) Profiles

- Commonly used to model the 2D spatial receptive field profiles of orientation tuned cells.
- Shape determined by spatial frequency ($\Omega$), width ($\sigma_x$, $\sigma_y$), orientation ($\theta$) and phase ($\phi$).
- Roughly speaking, describes the “best” stimulus for the neuron.

\[
\begin{bmatrix}
x' \\
y'
\end{bmatrix} = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
x \\
y
\end{bmatrix}
\]

\[
g(x, y) = \frac{1}{2\pi\sigma_x} \exp\left(-\frac{(x')^2}{2\sigma_x^2}\right) \cdot \frac{1}{2\pi\sigma_y} \exp\left(-\frac{(y')^2}{2\sigma_y^2}\right) \cdot \cos(\Omega x' + \phi)
\]

$\phi = 0^\circ$, $\sigma_y = 2\sigma_x$, $\sigma_x\Omega = 2$
Phase and Orientation Diversity

\[ \phi = 0^\circ \quad \phi = 90^\circ \quad \phi = 180^\circ \quad \phi = 270^\circ \]

\[ \theta = 0^\circ \quad \theta = 45^\circ \quad \theta = 90^\circ \quad \theta = 135^\circ \]

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The phase $f$ controls the type of stimulus (edge or bar) that best excites the detector.

Receptive fields with phases that differ $180^\circ$ are tuned to stimuli with opposite polarity (e.g. dark bars versus light bars).
Two phases is enough

- Cortical neurons display the full range of phases, although there is some evidence that phases cluster around 0°, 90°, 180° and 270°.
- RFs with $\phi = 0°$ (180°) are referred to as even-symmetric.
- RFs with $\phi = 90°$ (270°) are referred to as odd-symmetric.
- Theoretically, we can compute the output of any phase RF given the just the outputs of 0° and 270°:

$$\cos(\Omega x + \phi) = \cos(\Omega x)\cos(\phi) + \sin(\Omega x)\sin(\phi)$$

$$\phi = 0°$$
$$\cos(\Omega x)$$

$$\phi = 270°$$
$$\sin(\Omega x)$$

$\cos(\Omega x)$

$\sin(\phi)$

$\cos(\Omega x + \phi)$
V1 neurons are often differentiated as either
- “simple”: phase-dependent responses
- “complex”: phase-independent responses

Complex cells are often modelled as the sum of four simple cells with phase-quadrature RF profiles.
Phase and Orientation Diversity

\[ \theta = 0^\circ \quad \phi = 0^\circ \]

\[ \theta = 0^\circ \quad \phi = 90^\circ \]

\[ \theta = 0^\circ \quad \phi = 180^\circ \]

\[ \theta = 0^\circ \quad \phi = 270^\circ \]

\[ \theta = 45^\circ \quad \phi = 45^\circ \]

\[ \theta = 45^\circ \quad \phi = 90^\circ \]

\[ \theta = 45^\circ \quad \phi = 135^\circ \]

\[ \theta = 45^\circ \quad \phi = 180^\circ \]

\[ \theta = 45^\circ \quad \phi = 225^\circ \]

\[ \theta = 45^\circ \quad \phi = 270^\circ \]

\[ \theta = 45^\circ \quad \phi = 315^\circ \]

\[ \theta = 90^\circ \quad \phi = 0^\circ \]

\[ \theta = 90^\circ \quad \phi = 45^\circ \]

\[ \theta = 90^\circ \quad \phi = 90^\circ \]

\[ \theta = 90^\circ \quad \phi = 135^\circ \]

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\[ \theta = 135^\circ \quad \phi = 225^\circ \]

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\[ \theta = 135^\circ \quad \phi = 315^\circ \]
Video recap

input

Orientation.avi
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  - What is it?
  - How do we implement it?
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    - DSP/FPGA Architecture

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  - Disparity energy model: position versus phase shifts
  - Population responses versus tuning curves
  - Bigger is not necessarily better
Implementation: Design choices

- Continuous (asynchronous)
  - AER
  - Multichip

- Discrete (clocked)
  - DSP/FPGA
Orientation Hypercolumns

Multi-chip Model

Ice Cube Model
System Characteristics

- Retinotopic arrays of neurons with Gabor-type receptive fields
  - All neurons on one chip tuned to the same orientation and scale (electronically adjustable)
  - Phase quadrature receptive fields (EVEN and ODD)
  - Half wave rectification
- Continuous time operation
- Neurons on different chips communicate with spikes (AER)
Chip Data

- Neurons: 32x64x4 neurons (8000)
- Technology: TSMC 0.25um
- Die size: 3.84mm x 2.54mm (9.8mm²)
- Power dissipation: 3mW
Architectural Advantages

- Since neurons have identical response properties, retinotopic arrays are constructed by \textit{tiling}\n\textit{identical circuit blocks}.\n
- Neurons are only locally interconnected, which \textit{simplifies wiring}.\n
- ON-OFF and spike based representation, \textit{lowers power consumption and fixed pattern noise}.\n
- Continuous time operation enables \textit{feedback interactions between maps}.\n
Neuromorphic analogue of gap junctions
From one layer to two

In

Out

In

Odd

Even
ON/OFF Signal Representation

- Complementary channels encode positive and negative components of a signal
- Conserves metabolic resources by mapping background signals to near zero spike rates

Stimulus: on  
OFF cell

Stimulus: on  
ON cell

OFF cell

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From two layers to four

Even/ON
Odd/ON
Odd/OFF
Even/OFF
Even/ON
Odd/ON
Odd/OFF
In/ON
In/OFF
In

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Feedforward System

30,000 spiking neurons!
Odd Response to Ring

white = ON spikes    black = OFF spikes
The eventual system

Vertical Bars, Moving Left, At Fixation
Implementation: Design choices

- Continuous (asynchronous)
  - Analog
    - AER
    - Multichip
  - Digital
- Discrete (clocked)
  - DSP/FPGA
**Goal**

- **Rapidly reconfigurable** system for computing and combining outputs of many cortically inspired maps.
- Based on an expandable system architecture *that can be translated eventually to multi-chip AER neuromorphic systems*.
- Operates fast enough to support behavioral interaction with the environment.
System Architecture

Left Eye

Right Eye
Board Architecture

- **Neural Array Simulator**
- **USB Link**
- **Communication Controller**
- **PC**
- **TI 6414 600MHz**
- **32 MB SDRAM**
- **USB2.0**
- **LVDS**
- **GPIO**
- **4 MB SRAM**
- **Xilinx Spartan III**
- **Other Boards**

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Telluride Project (Vision Systems)

- First Board
  - Acquires image from camera at ~30fps
  - Computes Feature Maps
  - Converts to Spikes
  - Transmits to next board

- Second Board
  - Receives Spikes
  - Computes Additional Feature Maps
  - Transmits data to PC which integrates sensor information to generate behaviour

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PC for control
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Neural Array Simulator

USB Link

Communication Controller

PC for control
Speed

- Feature map computation (352 x 288 pixel images)
  - Edge map: 1.2ms
  - Gabor-like orientation map: 2.3ms
- Inter-board map transmission
  - 0.4ms (assuming an average of 5% spikes/frame)
Power dissipation

AER Based

- 45mW
  - Chip: 3mW (1% analog, 99% digital)
  - Support: 42 mW
- 8192 neurons, 1ms settling time
- 5.4nJ/(neuron*map)

DSP/ FPGA Based

- 3.5W
- 405,504 neurons, 2.3 ms map computation time
- 19.9nJ/(neuron*map)
Digital analogue of the gap junction

convolution?
integrate the differential equations?
Forward Backward Filtering

![Diagram of Forward Backward Filtering]

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Binocular disparity

- Image disparity is the relative displacement between image points in the left and right eyes corresponding to the same environmental point.
  \[ d = u_l - u_r \]

- Depth can be inferred from disparity and eye position.
  \[ \text{Depth} \propto \frac{1}{d} \]
Review: Orientation Energy

\[
\begin{align*}
\text{input image} & \quad \phi = 0^\circ \\
& \quad \phi = 90^\circ \\
& \quad \phi = 180^\circ \\
& \quad \phi = 270^\circ \\
\end{align*}
\]

is equivalent to:

\[
\begin{align*}
\text{input image} & \quad \phi = 0^\circ \\
& \quad \phi = 270^\circ \\
\end{align*}
\]
Binocular Energy Model

- Zero disparity tuned complex cell:

![Diagram of binocular energy model]

Position vs. phase shifts

- Position shifts:
  - center = -1
  - center = 0
  - center = 1

- Phase shifts:
  - $\phi = 90^\circ$
  - $\phi = 0^\circ$
  - $\phi = -90^\circ$
Tuning Curves vs. Population Responses

- Tuning curve: one neuron, many inputs
- Population responses: one input, many neurons
Phase-tuned populations are more reliable


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The disadvantage of phase-tuned neurons is that their preferred disparity range is limited by the periodicity of the cosine in the Gabor.

\[ \theta = 0^\circ \]

The measured disparities of V1 neurons ranges over a few degrees, but actual scene disparities range over tens of degrees.

Psychophysical results indicate that we fuse binocular stimuli only over a few degrees (Panum’s fusional area).
Detecting out of range disparities

- The mismatch between the small range of preferred disparities in cortex and the large range of scene disparities suggests that there should be a mechanism for detecting whether a population response is due to an input disparity “in the range” of preferred disparities or “out of the range”

- Unfortunately, this problem is complicated due to the fact that the tuning curves of disparity tuned neurons are not unimodal.
False peaks in phase-tuned populations

A

B

stimulus disparity (pixels)

population response to input with disparity 20

tuning curve of zero disparity tuned neuron

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Phase tuned population responses

The population response of a phase-tuned disparity neuron population depends on three parameters:
- $S =$ average activation
- $P =$ difference between peak and average activation
- $DF =$ peak location

Hypothesis: Since neurons respond strongly to their preferred inputs, if the average ($S$) activation or the difference between the peak and average activation ($P$) is large, the response is more likely to be reliable (i.e. “in the range”)
Bigger is not necessarily better

- **TPR** = true positive rate
  - The fraction of “in the range” inputs correctly classified

- **FPR** = false positive rate
  - The fraction of “out of range” inputs incorrectly classified as “in the range.”

- Thresholding S and P performs worse than chance, indicating that *smaller* responses are actually more indicative of “in the range” disparities.
Normalization enables robust validation

- $R = \frac{P}{S}$ performs reliably
  - The difference between the peak and average activation normalized by the average activation.

- Normalization is commonly used to account for nonlinear properties observed in cortical neurons.

- These results suggest a functional role for normalization.
**Statistical Analysis**

- $B_F = \text{Bayes factor for feature } F$: a measure of the evidence that the input disparity is "in the range" given the observed $F$.
  - $\log(B_F) > 0$: positive evidence for "in the range"
  - $\log(B_F) > 0$: positive evidence for "in the range"
Disparity Video

input  d = 0  d = 0  d = 1  d = 2

raw disparity energy

original image gated by R>T
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End of Presentation

Thanks for listening!

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- John ARTHUR (U. Penn)
Architectural Advantages

- Since neurons have identical response properties, retinotopic arrays are constructed by *tiling identical circuit blocks*.
- Neurons are only locally interconnected, which *simplifies wiring*.
- ON-OFF and spike based representation, *lowers power consumption and fixed pattern noise*.
- Continuous time operation enables *feedback interactions between maps*.
Conclusion

- We have developed digital hardware for real-time simulations of feature maps inspired by the visual cortex.
- This system is a rapidly reconfigurable test bed for investigating active visual perception based upon the outputs of model visual cortical columns.
- Algorithms and architectures developed on this hardware will guide the development of mixed signal neuromorphic chips, and multi-chip networks.
Conclusion

- We have developed silicon networks of neurons selective for position, spatial frequency, orientation and (binocular disparity or direction/speed of motion)

- Neurons support both feedforward and feedback interactions even though they may reside on different chips.

- The largest of these systems contains over 30,000 recurrently connected continuous-time neurons.

- Next step: Retinotopic arrays of neurons simultaneously selective for disparity and motion.
Active Binocular Tracking

**Version**
controlled by centroid of zero disparity cells

**Vergence**
controlled by difference between near and far disparity cells
Chip Data

- Neurons: 32x64x4 neurons (8000)
- Technology: TSMC 0.25um
- Die size: 3.84mm x 2.54mm (9.8mm²)
- Power dissipation: 3mW
Motion Energy Model

Spatial Filtering

Temporal Filtering

Spatio-Temporal Filtering
Estimation of Focus of Expansion

<table>
<thead>
<tr>
<th>Original Image</th>
<th>Horizontal Motion</th>
<th>-45° Motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated FOE</td>
<td>Vertical Motion</td>
<td>+45° Motion</td>
</tr>
</tbody>
</table>
Feedback System

- A global inhibitory neuron pools input across different orientations from neurons tuned to the same retinal location with the same polarity (ON/OFF) and symmetry (EVEN/ODD).
- The inhibitory neuron sends inhibition to the neurons that excite it.
Feedforward System

30,000 spiking neurons, all recurrently interconnected!
Shifts in orientation tuning

- Competition pushes orientation tunings apart

\[ \text{EVEN} \]

\[ \text{ODD} \]

\[ = \text{prediction} \]

\[ \times = \text{measured} \]
Model vs. Implementation

Model
- Graded interactions between neurons
- Linear model
- Perfect matching

Implementation
- Spike interactions between neurons
- Nonlinear model due to ON/OFF rectification
- Lots of mismatch
Applications

- Binocular tracking
- FOE estimation