Modeling shape selectivity beyond V1
COSFIRE operators

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Visual cortex
Visual cortex

Dorsal Stream
“where”
Visual cortex

Dorsal Stream
“where”

Ventral Stream
“what”
Visual cortex

Dorsal Stream
“where”

V1/V2

Ventral Stream
“what”
Visual cortex

Ventral Stream
“what”
Visual cortex

Ventral Stream
“what”
Area V4

V1

V2

V4
V4 neurons

- Selective for
  - Color  [Zeki, 1973]
  - Texture  [Hanazawa, 2001]
  - Shape  [Pasupathy, 1999]

Stimuli characterised by curvature and orientation
Shape-selective V4 neurons

[Pasupathy, 1999]
Population coding

A more complex shape can be represented by the collective responses of a group of V4 neurons

[Pasupathy, 2002]
TEO - Posterior inferotemporal cortex

V1
V2
V4
TEO
TEO - Posterior inferotemporal cortex

- [Brincat, 2004] studied 109 TEO neurons

- Selective for a combination of multiple contour elements
Computational models

Neurophysiology

- V1 (bars and edges)
  ![V1 bars and edges]

- V4 (vertices)
  ![V4 vertices]

- TEO (moderately complex)
  ![TEO moderately complex]
Computational models

Neurophysiology

- V1 (bars and edges)
- V4 (vertices)
- TEO (moderately complex stimuli)

Computer Vision

Gaussian/Gabor/CORF
### Computational models

#### Neurophysiology

<table>
<thead>
<tr>
<th>V1 (bars and edges)</th>
<th>V4 (vertices)</th>
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<tbody>
<tr>
<td><img src="image" alt="V1 bars" /></td>
<td><img src="image" alt="V4 vertices" /></td>
<td><img src="image" alt="TEO complex" /></td>
</tr>
</tbody>
</table>

#### Computer Vision

Gaussian/Gabor/CORF

?
A keypoint detector inspired by the function of V4 neurons

- Select a pattern of interest
A filter is automatically configured

- **Sub-units:** orientation-selective detectors
Step 1 of configuration: detect oriented stimuli

Given pattern
Step 1 of configuration: detect oriented stimuli

2D Gabor filters

Given pattern
Step 1 of configuration: detect oriented stimuli

2D Gabor filters

Given pattern
Step 1 of configuration: detect oriented stimuli

2D Gabor filters

Given pattern

Bank of Gabor filters
Step 2 of configuration: identify dominant orientations

How? Consider a superposition of Gabor responses
Step 2 of configuration: identify dominant orientations

- Consider Gabor responses along a circle of a given radius.
Step 2 of configuration: identify dominant orientations

- Identify significant local maxima
Step 2 of configuration: identify dominant orientations

- Result of analysis
  - $(\lambda, \theta)$ - line properties
  - $(\rho, \varphi)$ - position w.r.t. filter center
Increasing tolerance

Do not consider only the Gabor response in the red point, but also in nearby positions. This will allow you to detect not only vertical lines in the red point but also nearly vertical lines in nearby points.
Increasing tolerance

Do not consider only the Gabor response in the red point, but also in nearby positions. This will allow you to detect not only vertical lines in the red point but also nearly vertical lines in nearby points.
Step 3: Response of Sub-unit 1

If this filter responds strongly in the center point this means: "There is a (nearly) vertical line at (or near) point \((\rho, \varphi)\) from the center of the filter."
Step 3: Response of Sub-unit 2

If this filter responds strongly in the center point this means: "There is a (nearly) horizontal line at (or near) point \((\rho, \varphi)\) from the center of the filter."
Step 4: Filter response

Geometric mean

\[
\left\{ \begin{array}{c}
\star
\
\end{array} \right\} \frac{1}{2}
\]

Sub-unit 1

Sub-unit 2
Step 4: Filter response

Geometric mean

\[
\left\{ \begin{array}{c}
\text{Sub-unit 1} \\
\text{Sub-unit 2}
\end{array} \right\} \ast \frac{1}{2} = \text{Filter response}
\]
Step 4: Filter response

Geometric mean

\[
\left\{ \text{Sub-unit 1} \ast \text{Sub-unit 2} \right\}^{1/2} = \text{Filter response}
\]

Reconstruction
Step 4: Filter response

Geometric mean

\[
\left\{ \text{Sub-unit 1} \ast \text{Sub-unit 2} \right\} \frac{1}{2} = \text{Filter response}
\]

If the product of the two blurred and shifted Gabor filters is substantial in a given point, this means: "There is a (nearly) vertical line at a certain distance above and a (nearly) horizontal line at a certain distance to the left of the concerned point".
Set of elementary features used in neurophysiological study [Pasupathy, 1999]
[Pasupathy, 1999]
Filter selective for the original feature rotated by 90°.
Rotation-invariant responses
Detection of more complex patterns

Input Image
Detection of more complex patterns

The ellipses illustrate the identified relevant Gabor filters, the blobs illustrate their blur factor and the shift to the center.
Detection of more complex patterns

Input Image

Rotation-non-invariant
Detection of more complex patterns

Input Image

Rotation-non-invariant

Rotation-invariant
Summary of computational model/filter

- CORF model (Combination Of Receptive Fields)
  - simulates the properties of shape-selective V4 neurons
Summary of computational model/filter

- **CORF** model (**Combination Of Receptive Fields**)
  - simulates the properties of shape-selective V4 neurons

- **COSFIRE** filter (**Combination Of Shifted Filter Responses**)
  - Gabor filters $\rightarrow$ blur and shift $\rightarrow$ multiply
Summary of computational model/filter

- **CORF** model *(Combination Of Receptive Fields)*
  - simulates the properties of shape-selective V4 neurons

- **COSFIRE** filter *(Combination Of Shifted Filter Responses)*
  - Gabor filters $\rightarrow$ blur and shift $\rightarrow$ multiply

- **Trainable**
  - can be configured with any given local contour pattern
The structure of the retinal vascular tree can reveal signs of cardiovascular diseases

[Azzopardi, 2011]
Detection of bifurcations in retinal fundus images

This image contains 101 bifurcations
Configuration of a COSFIRE filter

User selects a pattern
Input pattern

Superimpose Gabor responses
Input pattern

Consider Gabor responses
Choose local maxima points
Input pattern

Extract parameter values
Input pattern

Tolerance: blurring functions
Input pattern

COSFIRE filter structure
Input pattern

\[ S_f = \{(\lambda_i, \theta_i, \rho_i, \varphi_i) \mid 1 \leq i \leq n_f\} \]
Apply the configured COSFIRE filter

Input image → Filter by Gabor functions → Blur Gabor responses → Shift the blurred Gabor responses → Combine by weighted geometric mean → Filter output
**COSFIRE**: Tolerant to geometric transformations

Rotation-tolerant

38 (out of 101) detected features
COSFIRE: Tolerant to geometric transformations

Rotation- and scale-tolerant

62 (out of 101) detected features
COSFIRE: Tolerant to geometric transformations

Rotation-, scale- and reflection-tolerant

85 (out of 101) detected features
Training

Detections by COSFIRE filter 1
Training

Choose a missed bifurcation

Enlarged selected bifurcation
Training

COSFIRE filter 2
Training

Detections by **COSFIRE filter 1**

85 out of 101 bifurcations

Detections by **COSFIRE filter 2**

82 out of 101 bifurcations
Training

Combined results of 2 COSFIRE filters

97 out 101 bifurcations
Training

100% Precision and 100% Recall for training
Testing

**DRIVE data set**

[DRIVE04]

image 1  image 2  image 40
Results

Results for the whole DRIVE data set
(40 images, more than 5000 bifurcations)
Results

Results for the whole DRIVE data set
(40 images, more than 5000 bifurcations)
Detection of vascular bifurcations in retinal fundus images using trainable COSFIRE filters

N. Petkov, G. Azzopardi and Zhe Sun, University of Groningen, Department of Computing Sciences, Intelligent Systems

Other on-line image processing and computer vision applications are available at http://matlabserver.cs.rug.nl.

On this site you can process a binary retinal image taken from the DRIVE data set [1] with some predefined COSFIRE filters, visualize the output of the filters rendered as a gray-level image, visualize the detected vascular bifurcations as encircled features in the input image, use the slider below the images to control the output of the COSFIRE filters, the number of detected features decreases with an increasing threshold value (i.e., moving the slider to the right), and download the output image with the detected features encircled as well as the coordinates of these detected features.

We are currently extending this application by including a facility to upload colour/binary retinal images, and an algorithm for automatic vessel tree segmentation of the uploaded images. In the near future, we will also include detailed explanations on the parameters of the COSFIRE filters.

Ground truth data of vascular bifurcations in retinal images of the DRIVE database

In http://www.cs.rug.nl/~maqna/databases/retina_database, we provide the (row, col) coordinates of the vascular bifurcations that were manually selected as ground truth data in 40 binary images of the DRIVE data set.
Handwritten digit recognition

**MNIST data set**
[LeCun, 1998]

60,000 training and 10,000 test digits
Configuration of COSFIRE filters

- Choose a subset of random images from each digit class
- Choose a random location in each selected digit image
Recognition rate: 99.48%
Handwritten digit recognition

Farsi data set: 99.33%
[Khosravi, 2007]

60,000 training and 20,000 test digits
Detection and recognition of traffic signs

RuG data set
[Grigorescu, 2003]
Configuration of COSFIRE filters
Data set of 48 grayscale images
Detection and recognition rates: 100%
Keypoint detection for geometric camera calibration

<table>
<thead>
<tr>
<th>Detector</th>
<th>Zhang’s method: $RMS$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harris</td>
<td>1.1239</td>
</tr>
<tr>
<td>COSFIRE</td>
<td>0.6417</td>
</tr>
</tbody>
</table>

2D planar objects

[Capozzoli et al, 2012]
(A) A prototype shape. (B) A test pattern that has only 25% similarity (computed by template matching) to the prototype is perceptually more similar to the prototype than the polygon in (C) and the set of contour parts in (D), both of which have 50% similarity (computed by template matching) to the prototype.
(A–D) A set of stimuli used in an electrophysiological study Kobatake and Tanaka (1994) to test the selectivity of a neuron in inferotemporal cortex. (Bottom) The activity of the concerned neuron for the corresponding stimuli. The neuron gives high response only when the stimulus contains a detailed or simplified representation of the face boundary that surrounds a pair of eyes on top of a mouth. If any of these features is missing, the neuron gives negligible response.
Configuring a Filter
Application
Keyword spotting in handwritten manuscripts

There they have stayed uselessly locked up because Germany has no tradition of trading abroad. In addition the strength of Germany’s trading position has attracted speculators to hold marks rather than pounds or dollars, hoping for the mark to rise, as has now happened. Will the new valuation be enough to correct Germany’s massive trading surplus and choke off speculation against dollar and pound?

Booming Germany is deliberately encouraging more imports as a means to curb rising prices at home. She is also aware how unpopular she has been growing by failing until now to co-operate as a creditor nation. Should Germany export much more than she imports. For upwards of five years the world’s reserves of dollars have been drained into Germany.

Germany
Keyword spotting in handwritten manuscripts

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Vision for home tidying pickup robot
Vision for home tidying pickup robot
Conclusions

- **COSFIRE filter and CORF model:**
  - Inspired by shape-selective V4 neurons
Conclusions

- **COSFIRE** model:
  - Inspired by shape-selective V4 and TEO neurons

![COSFIRE model diagram]

- **Simple implementation:**
  - Gabor filters → blur and shift → multiply
Highly **effective** and **versatile** detectors

- Retinal bifurcations
- Handwritten digits
- Traffic signs
- Camera calibration
- Robot vision
- Keyword spotting
Outlook

- Feedback mechanism
- Learning of parameters
  - Blurring function
  - Output function
  - Optimal number of tuples
    - E.g. using Genetic Algorithms

I’m looking for students!

Matlab code of COSFIRE

http://tinyurl.com/p5gklaw
Psychophysics

Curved contour parts are detected by multiplication

[Gheorghiou 2009]