Visual Texture: Discrimination, Pattern Identification and Cortical Coding

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Broad Outline

- 2\textsuperscript{nd}-order channels: Psychophysics and fMRI

- Optional: Visual perception of surface roughness

- Other current work: Statistics of natural textures and psychophysics
Outline

• 2\textsuperscript{nd}-order channels
  \((Vis\ Res\ 2002)\)

• 2\textsuperscript{nd}-order letter recognition
  \((Vis\ Res\ 2006)\)

• 2\textsuperscript{nd}-order cortical coding
  \((J\ Neurophys\ 2006,\ J.\ Neurosci\ in\ press)\)
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• 2\textsuperscript{nd}-order channels
  \textit{(Vis Res 2002)}

• 2\textsuperscript{nd}-order letter recognition
  \textit{(Vis Res 2006)}

• 2\textsuperscript{nd}-order cortical coding
  \textit{(J Neurophys 2006, J. Neurosci in press)}
Neurons in primary visual cortex (V1) extract boundary information

Properties of visual boundaries:

- orientation
- position
- scale
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Properties of visual boundaries:

- orientation
- position
- scale
Boundary types in visual scenes: 
**first-order** and **second-order**

- **First-order:** vary in luminance
- **Second-order:** do *not* vary in luminance
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Second-order boundaries are invisible to first-order (V1) neurons

- Many different types of second-order boundaries: changes in contrast, texture, orientation, scale, motion; illusory contours...
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Luminance Edge  

Texture Edge
Computational models of boundary perception: filter-rectify-filter (FRF)

**First stage:** many small-scale first-order receptive fields

**Rectify** (threshold) output of first stage

**Second stage:** Sum rectified output with large-scale receptive field
The contrast sensitivity function (CSF)

(Campbell & Robson, 1968)
Back-pocket model
Typical Stimulus for measuring CSF: Sine wave grating
Typical Stimulus for measuring CSF: Sine wave grating
2\textsuperscript{nd}-order summation experiment:
Summary – 2nd-order detection

- Flat CSF
- Multiple 2nd-order channels
- ~1.5 octaves bandwidth
Outline

• 2\textsuperscript{nd}-order channels
  (Vis Res 2002)

• 2\textsuperscript{nd}-order letter recognition
  (Vis Res 2006)

• 2\textsuperscript{nd}-order cortical coding
$1^{st}$-order letter identification
Information is available for letter identification at many frequencies
• Solomon & Pelli, 1994. Channels for letters?

*Critical band masking* paradigm.
• Solomon & Pelli, 1994. Channels for letters?

Critical band masking paradigm.

**Stimulus:** Sinewave grating  **Task:** Detection
• Solomon & Pelli, 1994. Channels for letters? 

**Critical band masking paradigm.**

**Stimulus:** Sinewave grating  
**Task:** Detection

**Stimulus:** Letter
Channels for letters? Critical band masking paradigm.

**Stimulus:** Sinewave grating  
**Task:** Detection

**Stimulus:** Letter  
**Task:** Identification

• Solomon & Pelli, 1994. Channels for letters?

Critical band masking paradigm.

**Stimulus:** Sinewave grating  **Task:** Detection

**Stimulus:** Letter  **Task:** Identification

![Sinewave grating](image1)

![Spatial frequency](image2)
Channels for letters?

Critical band masking paradigm.

Stimulus: Sinewave grating  Task: Detection

Stimulus: Letter  Task: Identification
• Solomon & Pelli, 1994. Channels for letters?

*Critical band masking* paradigm.

**Stimulus:** Sinewave grating  **Task:** Detection

**Stimulus:** Letter  **Task:** Identification

**Critical band masking paradigm.**

**Stimulus:** Sinewave grating  
**Task:** Detection

**Stimulus:** Letter  
**Task:** Identification
Off-frequency looking?
Off-frequency looking?
Off-frequency looking?

stroke frequency for letters

\[ Z \rightarrow z \]
\[ \gamma \rightarrow \gamma \]

Stroke frequency for letters increasing channel frequency

\[ Z \rightarrow z \rightarrow \varphi \rightarrow \psi \]
stroke frequency for letters

increasing channel frequency

\[ \text{incr channel freq} \]

\[ \begin{array}{c}
\text{Z} \\
\text{z} \\
\text{g} \\
\text{g}
\end{array} \]
stroke frequency for letters

scale dependence in letter recognition!

stroke frequency for letters

scale dependence in letter recognition!
2\textsuperscript{nd}-order letter identification
• Channels for 2\textsuperscript{nd}-order letters?
• Off-frequency looking?
• Scale-dependence?
• Channels for 2\textsuperscript{nd}-order letters?
• Off-frequency looking?
• Scale-dependence?
• Channels for 2\textsuperscript{nd}-order letters?
• Off-frequency looking?
• Scale-dependence?
Task: Letter identification
Choice of letter stimuli

Ink area (%)

Letters of the alphabet

V  C  O  K  H  N  Z  D  R  S
Critical band masking paradigm (Solomon & Pelli, 1994)
threshold elevation

noise cut-off frequency

channel

noise

target

energy

frequency
channel

target

noise

frequency

energy

threshold elevation

noise cut-off frequency
noise
channel
target
energy
frequency
threshold elevation
noise cut-off frequency
channel
target
noise
frequency
threshold elevation
energy

noise cut-off frequency

channel

target
channel

noise
target

energy

frequency

threshold elevation

noise cut-off frequency
channel

noise
target

energy

frequency

threshold elevation

noise cut-off frequency
Low-pass noise conditions
Check for signs of off-frequency looking: Test *Noise additivity*

- **Threshold elevation: $E^*_L$**
- **Threshold elevation: $E^*_H$**

If fixed channel, $E^*_{ALL} = E^*_L + E^*_H$

Otherwise, $E^*_{ALL} > E^*_L + E^*_H$
Noise additivity graphs

Sum of SNR* for complementary low- and high-pass noises

Noise cut-off frequency (cycles / letter)
Threshold elevation graphs

Noise cut-off frequency (cycles / letter)
Derived channels

- HB: center = 13.2, bw = 1.8
- IO: center = 12.9, bw = 2.7
- JT: center = 17.7, bw = 1.2
- MSL: center = 16.1, bw = 0.6
- IO 3X distance: center = 15.2, bw = 1.0
- IO Half Distance: center = 15.9, bw = 1.1
- MSL Half distance: center = 18.6, bw = 1.2
- MSL 2X distance: center = 17.2, bw = 1.3

Normalized sensitivity vs. Spatial frequency (cycles / letter)
The data for a given carrier frequency superimpose.

But, the channel frequency scales with the carrier frequency.

We next define a “letter texture stroke frequency” that treats the texture carrier as if it is intrinsic to the font.
Results

Like 1st-order letters:
Stroke frequency determines channel

Unlike 1st-order letters:
Scale invariant
Lower frequency channels relative to stroke frequency
Summary: 2nd-order letter identification

- 2^{nd}-order letters are identified using a single channel
- No off-frequency looking
- Scale invariance (but …)
Outline

- 2nd-order channels
  (Vis Res 2002)

- 2nd-order letter recognition
  (Vis Res 2006)

- 2nd-order cortical coding
  (J Neurophys 2006,
   J. Neurosci in press)
Neural mechanisms of mid-level vision
Neural mechanisms of mid-level vision

Primary visual cortex (V1)
Neural mechanisms of mid-level vision

Primary visual cortex (V1)

Dorsal stream

Ventral stream
Neural mechanisms of mid-level vision

Primary visual cortex (V1)

ventral stream
Neural mechanisms of mid-level vision

Primary visual cortex (V1)

ventral stream

Higher visual areas
Neural mechanisms of mid-level vision

Primary visual cortex (V1)

Higher visual areas
Neural mechanisms of mid-level vision

Primary visual cortex (V1)

Higher visual areas

???
Neural mechanisms of mid-level vision

Primary visual cortex (V1)

Higher visual areas

??

??
Computational models of boundary perception: filter-rectify-filter (FRF)

First stage: many small-scale first-order receptive fields

Rectify (threshold) output of first stage

Second stage: Sum rectified output with large-scale receptive field
Computational models of boundary perception: filter-rectify-filter (FRF)

**First stage**: many small-scale first-order receptive fields

**Rectify** (threshold) output of first stage

**Second stage**: Sum rectified output with large-scale receptive field

- Predicts *separate* mechanisms for first-order and second-order boundary perception
- Predicts *selectivity for orientation, location, scale*
Nice model, but...
Nice model, but...

- ...this is all based on psychophysics and single-unit recordings in cats and monkeys

- Q. How do we identify *neural correlates* of boundary perception - e.g., orientation selectivity - in the human brain?

- A. Use functional MRI (fMRI) to measure orientation-selective adaptation
Orientation-selective adaptation to first-order boundaries in V1 revealed by fMRI
Identifying orientation-selective neuronal populations with selective adaptation

Before adaptation

Preferred stimulus

\[ V = H \]

Response to preferred stimulus
Identifying orientation-selective neuronal populations with selective adaptation

Preferred stimulus

Before adaptation

After adaptation to vertical

Response to preferred stimulus

\[ V = H \]

\[ V < H \]
Identifying orientation-selective neuronal populations with selective adaptation

**Preferred stimulus**

- **V** — Before adaptation
- **H** — After adaptation to vertical
- **V** — After adaptation to horizontal

**Response to preferred stimulus**

- **V = H**
- **V < H**
- **H < V**
Identifying orientation-selective neuronal populations with selective adaptation

Preferred stimulus

Before adaptation

After adaptation to vertical

After adaptation to horizontal

Response to preferred stimulus

\[ V = H \]

\[ V < H \]

\[ H < V \]

- Only orientation-selective neurons will respond more weakly to adapted orientation.
Identifying retinotopic visual areas

- Identify areas containing a retinotopic map of the visual field
- Standard phase-encoded retinotopic mapping methods
Identifying retinotopic visual areas

- Identify areas containing a retinotopic *map of the visual field*
- Standard phase-encoded retinotopic mapping methods
Identification of retinotopic visual areas using periodic stimuli

Eccentricity

Polar angle
Retinotopic visual areas and regions of interest (ROIs)
Retinotopic visual areas and regions of interest (ROIs)
Orientation-selective adaptation in V1 revealed by fMRI
Stimulus conditions

**First-order**
- LM:LM
  - luminance

**Second-order**
- CM:CM
  - contrast
- OM:OM
  - orientation
## Trial types

<table>
<thead>
<tr>
<th></th>
<th>Adapter orientation</th>
<th>Probe orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parallel trials</strong></td>
<td><img src="image" alt="Parallel trials" /></td>
<td><img src="image" alt="Parallel trials" /></td>
</tr>
<tr>
<td><strong>Orthogonal trials</strong></td>
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<td><img src="image" alt="Orthogonal trials" /></td>
</tr>
<tr>
<td><strong>Blank trials</strong></td>
<td><img src="image" alt="Blank trials" /></td>
<td>blank screen</td>
</tr>
</tbody>
</table>
**Trial structure**

<table>
<thead>
<tr>
<th>Adapter</th>
<th>ISI</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 s</td>
<td>1 s</td>
<td>1 s</td>
</tr>
</tbody>
</table>

**Unattended perifoveal stimulus**
(1.5-5 deg)

7.2 s
**Trial structure**

**Unattended perifoveal stimulus** (1.5-5 deg)

**Attended foveal RSVP task** (<1 deg)

Adapter 4 s  ISI 1 s  Probe 1 s  Response 1.2 s

how many X's?

Unattended perifoveal stimulus (1.5-5 deg)

Attended foveal RSVP task (<1 deg)

ZLNTZLNTZXNTXL..........NXZLNTZ 0.15 s

7.2 s
fMRI methods

- 3 subjects
- 8 scanning sessions per subject
- 280 trials per stimulus condition and trial type
- Siemens Allegra 3T, quadrature surface coil
- BOLD EPI, 19 slices perpendicular to calcarine sulcus, TR=1.2s, TE=30ms, FA=75
- Bite bar & motion correction with FSL
Adaptation to first-order boundaries (LM:LM)
Measuring amplitude of orientation-selective adaptation

![Graph showing FMRI response over time with orthogonal and parallel trials, showing modulation effects.](image)
Measuring amplitude of orientation-selective adaptation

**Graph:**
- **Y-axis:** FMRI response (% modulation)
- **X-axis:** Time (s)
- **Legend:**
  - **Adapter** in blue
  - ** Probe** in orange

**Trial Type:**
- **Parallel**
- **Orthogonal**

**V1**
Orientation-selective adaptation to first-order boundaries in multiple visual areas

![Graph showing FMRI response amplitude for different visual areas with parallel and orthogonal boundaries.](chart.png)
Orientation-selective adaptation to first-order boundaries in multiple visual areas
Orientation-selective adaptation to first-order boundaries in multiple visual areas

- **Parallel**
- **Orthogonal**

![Graph showing FMRI response amplitude (% modulation) for various visual areas (V1, V2, V3, hV4, VO1, pLOC, LO1, LO2, V3A/B, V7, V5). The graph highlights significant differences marked with *** and **.](image-url)
Orientation-selective adaptation to first-order boundaries in multiple visual areas

![Graph showing FMRi response amplitude (% modulation) for different visual areas.](image)
Orientation-selective adaptation to first-order boundaries in multiple visual areas

Adaptation index:

\[ I_A = \frac{A_\perp - A_\parallel}{|A_\perp| + |A_\parallel|} \]
Adaptation to first-order boundaries is constant across visual areas

LM

Adaptation index
Adaptation to first-order boundaries is constant across visual areas

LM

Adaptation index

Visual area

V1  V2  V3  hV4  VO1  LO1  V3A/B

0.8
0.6
0.4
0.2
0

V1  V2  V3  hV4  VO1  LO1  V3A/B
Adaptation to first-order boundaries is constant across visual areas

- Adaptation indices constant across visual areas
- Adaptation in V1 can account for adaptation in extrastriate visual areas
Adaptation to second-order boundaries (CM:CM & OM:OM)
Adaptation to second-order boundaries: contrast (CM:CM)

![Graph showing FMRI response amplitude (in % modulation) for various brain regions (V1, V2, V3, hV4, V2A, pLOC, LO1, LO2, V3A/B, V7, V5) under parallel and orthogonal conditions. The graph includes error bars and statistical significance markers (*, **, ***). The parallel condition shows a higher response amplitude compared to the orthogonal condition for most regions.](image-url)
Adaptation to second-order boundaries: orientation (OM:OM)
Adaptation to second-order boundaries increases beyond V1.
Adaptation to second-order boundaries increases beyond V1

- Suggests additional adaptation beyond V1
Filter-rectify-filter (FRF) model

**First stage:** V1

**Rectify** (threshold) output of V1

**Second stage:** Visual areas beyond V1
Filter-rectify-filter (FRF) model

*First stage:* $V1$

*Rectify* (threshold) output of $V1$

*Second stage:* Visual areas beyond $V1$

- Predicts *no* cross-adaptation between first-order and second-order boundaries
Cross-modal adaptation

(LM:OM)
No cross-adaptation between first- and second-order boundaries (LM:OM)
Psychophysical measures of orientation-selective adaptation mostly matches fMRI adaptation.
Illusory contour stimuli

Carrier (line inducers)

Control stimulus (line inducers misaligned)

3.5°

time
Orientation-selective adaptation to illusory contours in V1 and beyond
Adaptation increases beyond V1
- and is specific to illusory contours

Adaptation Index

Illusory contour adapter

Control (jittered adapter)

N=4
Conclusions: fMRI Study
Conclusions: fMRI Study

- Neural mechanisms of second-order boundary perception *consistent* with FRF model:
Conclusions: fMRI Study

• Neural mechanisms of second-order boundary perception consistent with FRF model:

First-order (first-stage) neurons in V1
Conclusions: fMRI Study

• Neural mechanisms of second-order boundary perception consistent with FRF model:

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  *Second-order (second-stage) neurons in mid-level visual areas (LO1, VO1, hV4, V3A/B) (and in V1)*
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• *Different* second-order patterns processed in *same* visual areas - consistent with single second-order mechanism
Conclusions: fMRI Study

• Neural mechanisms of second-order boundary perception consistent with FRF model:
  
  *First-order (first-stage) neurons in V1*

  *Second-order (second-stage) neurons in mid-level visual areas (LO1, VO1, hV4, V3A/B) (and in V1)*

  *No cross-adaptation from first- to second-order*

• *Different* second-order patterns processed in *same* visual areas - consistent with single second-order mechanism

• Selective attention is not required for first- or second-order pattern adaptation
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