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Approaches to Understanding Vision

Natural tasks

Natural scene statistics
Anatomy
Responses of individual neurons
Responses of neural populations
Perceptual/behavioral performance
Mathematical and computational modeling
Vision is very important for human survival. It involves many important and complex tasks.

**Important Visual Tasks**

- Identification of objects and materials
- Navigation through the environment
- Prediction of motion trajectories
- Estimation of physical dimensions
- Object manipulation
- Visual communication
Object Identification Task

A

B
Contour Completion Task

Do contour elements intersecting an occluding surface belong to the same or different contour?

A typical natural sub-task.
Another typical natural sub-task. Image contours can occur for a number of entirely different physical reasons. They can be the result of surface boundaries, surface markings or shading. There can be little doubt that many perceptual tasks depend critically upon identifying whether a contour is a surface boundary, a marking or a shadow.
Approaches to Understanding Vision

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**Natural scene statistics**

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Why Measure Natural Scene Statistics?

Characterize natural stimuli

Identify sources of stimulus information available for performing natural tasks

Determine the dynamic range, reliability and utility of the stimulus information

Generate hypotheses for visual mechanisms that might exploit the stimulus information

Design experiments to test for the hypothesized mechanisms
Here is another example where the red value at each pixel location is estimated from the blue and green values, using the average statistics of natural images.

The brain exploits this type of statistical regularity to improve the accuracy of our perceptions.
There is much statistical regularity in natural stimuli. For example, each pixel in an image has a value of red, green and blue. But the color in images is so predictable that it is possible to guess a missing color value pretty well if you know the other two values. In the bottom image the blue value at each pixel location has been guessed from the red and green values, using knowledge of the average statistics of natural images.
A

<table>
<thead>
<tr>
<th>Within domain</th>
<th>Across domain</th>
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<tbody>
<tr>
<td>Environment</td>
<td>$p(\omega)$</td>
</tr>
<tr>
<td>Image</td>
<td>$p(s)$</td>
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<td>Neural response</td>
<td>$p(z)$</td>
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<td>Behavior</td>
<td>$p(r)$</td>
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B

$\omega =$ fruit
$\omega =$ leaf

Environment $\Rightarrow$ Image

$\omega =$ fruit
$\omega =$ leaf

given fruit
given leaf

intensity
intensity
wavelength
wavelength
An example of absolute statistics. Distribution of edge orientation in images collected in different environments.
Example of across-domain statistics. From range-finder measurements, one can determine the probability of different distances given different image locations (relative to a line in the horizontal plane). The range image in A and probability distributions in B are from Huang, Lee and Mumford (2000). The plot in C is from Yang and Purves (2003).
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Cross section of the human retina. In this figure, light would reach the receptors from below (i.e., through the other cells in the retina). Dowling, J. E. (1987). The Retina: An approachable part of the brain. Cambridge, MA, Belknap Press.
Major connections between visual cortical areas. The width of the connection is proportional to the number of axon fibers. The upper side (warm colors) is the so-called “where pathway” and the bottom side (cool colors) is the so-called “what pathway.” These pathways have been determined from anatomical measurements (including injecting different areas with tracers).
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There are many different types of neurons but they share important features.
An electrode next to a pyramidal cell (a projection neuron) in the visual cortex.
Some basics of single neuron behavior and single neuron recording.
Electrical activity of a muscle reflex: from the stretch receptor to muscle contraction.
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Functional Imaging: What is measured?

Positron Emission Tomography (PET):
   Radioactive marker concentration

Functional Magnetic Resonance Imaging (fMRI):
   Blood oxygen level (BOLD signal)

Optical Imaging:
   Reflectance or fluorescence
PET images demonstrating how localization of activity can change depending on the task.
Demonstration of how fMRI can be used to quantify brain activity in specific brain locations in humans.
Optical imaging of primary visual cortex while a monkey performed a simple reaction time detection task. An hour long talk could easily be devoted to this study.

Records summed membrane potentials in the superficial (output layers of the cortex). Response distributed over a large population.
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Different perceptual tasks can be classified by picking one attribute from each column.
Example of an objective identification task with feedback. If there are just two alternatives, then such tasks are often called a *discrimination tasks*; if one of the alternatives is “uniform” in some fashion, then such tasks are often called a *detection tasks*. A typical stimulus presentation sequence for a single interval two-alternative forced choice experiment.
In the two interval task the observer must decide whether a target pattern is in the first temporal interval or the second temporal interval.
Illustration of the two-interval two-alternative forced choice task and the concept of the psychometric function.
A real example of a psychometric function. Each data point represents the proportion correct for a block of 30 trials.
The logic of measuring discrimination thresholds. The measurements are focused on the transition zone between the indistinguishable and the trivially easy to distinguish.
An objective identification task with no feedback. The illusion in this example is called the Müller-Lyer illusion. Such illusions have also been studied with descriptive methods (the phenomenological approach).
Example psychometric function for an objective task with no feedback.
Example of an objective estimation task with no feedback. The gray scale (luminance) is the same for the two squares in the checkerboard; in fact, it is exactly the same gray shown at the tails of the arrows. One way to estimate the difference in apparent luminance is to adjust the luminance of a comparison patch (against a same fixed background) to match the brightness of the squares in the two regions of the image. The luminance of the lighter comparison patch has an apparent luminance more similar to the square in the “shadow.” The difference in the physical luminance of the comparison gives a precise measure of the apparent (psychological) luminance difference.
Generalized Gaussian Psychometric Function

\[ F(x; u, \alpha, \beta, \gamma) = (1 - \gamma) \Phi\left( \frac{1}{2} \text{sign}(x-u) \left( \frac{|x-u|}{\alpha} \right)^\beta \right) + 0.5 \gamma \]

where:

- \( u \) = PSE
- \( \alpha = 70\% \) threshold
- \( \beta \) = shape (kurtosis) parameter
- \( \gamma \) = lapse rate

\[ \Phi(x) = \frac{1}{\sqrt{2\pi}} \exp\left( -\frac{1}{2} x^2 \right) \] is the standard normal integral function.
The likelihood of a particular sequence of responses from an observer, assuming statistical independence across trials. Maximum likelihood parameter estimation is to find parameter values that maximize the likelihood of the observed data.
Generalized Gaussian Psychometric Function

\[ F(x; u, \alpha, \beta, \gamma) = (1 - \gamma) \Phi \left( \frac{1}{2} \text{sign}(x-u) \left( \frac{|x-u|}{\alpha} \right)^\beta \right) + 0.5 \gamma \]

- \( u = 0 \) 
- \( \alpha = 70\% \) threshold 
- \( \beta = \) shape (slope) parameter 
- \( \gamma = \) lapse rate

\[ \Phi(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{1}{2} t^2 \right) dt \] 
standard normal integral function
The likelihood of a particular sequence of correct and incorrect responses from an observer, assuming statistical independence across trials. Maximum likelihood parameter estimation is to find parameter values that maximize the likelihood of the observed data.
Table of possible stimulus response outcomes in a 2AFC or a Yes/No task. For a summary of basic signal detection theory see Wickens, T. (2002) Elementary Signal Detection Theory. Oxford University Press (available online through the UT library).
Ideal (Bayesian) Decision Rule

Possible stimulus categories: $a, b$

Prior probability: $p(a), p(b)$

Stimulus likelihood: $p(S|a), p(S|b)$

Rational decision rule:

pick category $b$, if and only if $p(b|S) > p(a|S)$

or equivalently,

pick category $b$, if and only if $p(S|b) / p(S|a) > p(a) / p(b)$

or equivalently,

pick category $b$, if and only if $\ln \left( \frac{p(S|b)}{p(S|a)} \right) > \ln \left( \frac{p(a)}{p(b)} \right)$
Derivation of signal detection theory model of 2AFC data for the case of 1D Gaussian sensory input. The same final result is obtained with nD Gaussian sensory input.
Z is the decision variable, \( d' \) is the number of standard deviations separating the means of the two distributions, and \( c^* \) is the decision criterion.
Rewriting in terms of $d'$. 

$$Z = \ln \left( \frac{p(S|b)}{p(S|a)} \right)$$

$$d' = \frac{|u_a - u_b|}{\sigma}$$

$$c^* = \ln \left( \frac{p(a)}{p(b)} \right)$$
Now rescale the axes into units of standard deviation. This is the standard representation for signal detection theory. Within this representation, the proportions of hits and false alarm rates are used to estimate $d'$ and $c$. 

$$Z' = \ln \left( \frac{p(S|b)}{p(S|a)} \right) 1/d'$$

$$d' = \frac{|\mu_a - \mu_b|}{\sigma}$$

$$c = \ln \left( \frac{p(a)}{p(b)} \right) 1/d'$$
Signal Detection Theory Formulas

\[ d' = \Phi^{-1}(PC_{y}) - \Phi^{-1}(PE_{y}) \quad d' = \Phi^{-1}(P_{a}) - \Phi^{-1}(P_{\mu}) \]

\[ c = \Phi^{-1}(PC_{y}) - \frac{d'}{2} \quad c = \Phi^{-1}(P_{\sigma}) - \frac{d'}{2} \]

\[ PC_{y} = \Phi\left(\frac{d' - c}{2}\right) \quad \Phi_{a} = \Phi\left(\frac{d' - c}{2}\right) \]

\[ PE_{y} = \Phi\left(-c - \frac{d'}{2}\right) \quad \Phi_{\mu} = \Phi\left(-c - \frac{d'}{2}\right) \]

where,

\[ \Phi(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \]
Receiver Operating Characteristic (ROC)
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Computational/Mathematical Approaches

Descriptive models

Information processing models

Physiological models

Ideal observer analysis
Value of Ideal Observer Analysis

1. Identifying task-relevant stimulus properties

2. Describing how to use those properties to perform the task

3. Providing a benchmark against which to compare the performance of real or model vision systems

4. Suggesting principled hypotheses and models for real performance
Ideal Bayesian observers provide a useful conceptual and modeling framework for understanding the design of perceptual systems.
Ideal Bayesian observers provide a useful conceptual and modeling framework for understanding the design of perceptual systems. Note that the constant in the front of the summation does not affect the optimal response and hence can be set to 1.0.

Ideal Bayesian Observer
(general case)

State of environment: \( \omega \)
Stimulus: \( S \)
Response: \( r \)

make the response \( r \) that maximizes:

\[
\overline{r}(r|S) = k_S \sum_{\omega} \gamma(r, \omega) p(S|\omega) p(\omega)
\]

utility (cost) function  stimulus likelihood  prior probability
Ideal Bayesian Observer
(categorization task)

Possible stimulus categories: \( c_1, c_2, \cdots, c_n \)

Prior probability: \( p(c_i) \)

Posterior probability: \( p(c_i|S) \)

Rational decision rule:

make response \( i \), if \( p(c_i|S) > p(c_j|S) \), for all \( i \neq j \)
Ideal Bayesian Observer

categorization task

Possible stimulus categories: $c_1, c_2, \ldots, c_n$

Prior probability: $p(c_i)$

Stimulus likelihood: $p(S|c_i)$

Rational decision rule:

pick category $i$, if $p(S|c_i) p(c_i) > p(S|c_j) p(c_j)$, for all $i \neq j$
Logic of Bayesian approach (Sinha & Adelson 1993).
Bayesian statistical decision theory as a framework for studying perception. From Geisler & Kertsen (2002)
Knill and Kersten demonstration of the effects of geometrical cues on perceived lightness. Illusions may represent rational inferences by the perceptual systems.
Subjective/illusory contours of the sort designed by Kanizsa.
R. C. James’ picture that demonstrates the importance of learning in perception. Knowledge of prior probabilities can be learned as well as inherited.
Ideal Bayesian observers provide a useful conceptual and modeling framework for understanding the design of perceptual systems. They can include constraint functions to represent known anatomical and physiological constraints.

\[
\tilde{\gamma}(r|Z) = \sum_{\omega} \gamma(r,\omega) p(\omega|Z)
\]

utility function  posterior probability
Natural Systems Analysis

1. Identify and characterize natural tasks

2. Measure and analyze relevant environmental properties (e.g., measure natural scene statistics) and biological/physical constraints

3. Determine how to exploit the measured environmental properties to perform natural tasks optimally, given the biological/physical constraints

4. Formulate hypotheses and test them in physiological and behavioral studies that capture the essence of the natural task
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