Sensory Decoding

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Stimulus | Neural response | Behavior

“Encoding”
Transform and represent sensory information

“Decoding”
Extract encoded information for estimation/decision/action

Decoding (a.k.a. “read-out”) rules

- Winner-take-all
  \[ \hat{s}(\vec{r}) = s_m, \quad m = \arg \max_n \{ r_n \} \]

- Population vector [Georgopoulos et al., 1986]
  \[ \hat{s}(\vec{r}) = \frac{\sum_m r_n s_n}{\sum_n r_n} \]
Linear population decoding
[Kalaska, Caminiti Georgopoulos, 1983]

A sum of vectors, weighted by firing rate, predicts arm movement...

Response to wind direction of 4 cercal cricket interneurons [Theunissen & Miller '91]

Linear population decoding, cricket cercal interneurons [Salinas & Abbott '94]
Decoding (a.k.a. “read-out”) rules

- Winner-take-all \( \hat{s}(\vec{r}) = s_m, \quad m = \arg \max_n \{ r_n \} \)

- Population vector \[ \text{[Georgopoulos et al., 1986]} \quad \hat{s}(\vec{r}) = \frac{\sum_n r_n s_n}{\sum_n r_n} \]

- Maximum likelihood \( \hat{s}(\vec{r}) = \arg \max_s p(\vec{r}|s) \)

- Bayesian (MAP) \( \hat{s}(\vec{r}) = \arg \max_s p(\vec{r}|s) \cdot p(s) \)

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The scientist’s perspective

\[ P(\text{resp} \mid \text{stim}) \]

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The organism’s perspective

\[ P(\text{stim} \mid \text{spikes}) \]

The organism must “read” noisy responses, infer something about the stimulus, and respond (make judgements about it, remember it, or act on it).
Helmholtz (1866)

Perception is our best guess as to what is in the world, given our current sensory input and our prior experience [paraphrased]

Bayesian perception

world  observer

measurement  estimate

v → m → ŵ

noise! memory

“Encoding”  “Decoding”

P(m|v)
Bayesian perception

Bayesian humans?

- Shading/lighting [Kersten 90; Knill, Kersten, Yuille 96; Mamassian, Landy, Maloney 01]
- Motion [Simoncelli 93; Weiss et al. 02; Stocker & Simoncelli 06]
- Surface orientation [Bülthoff & Yuille 96; Saunders & Knill 01]
- Color constancy [Brainard & Freeman 97]
- Contours [Geisler, Perry, Super 01]
- Sensory-motor tasks [Körding & Wolpert 04]

II. Motion estimation
The "Thompson effect"

Contrast affects perceived speed

[Thompson '82]

Which is faster?

Effect increases with contrast ratio, decreases with speed

[Stocker & Simoncelli, '06]
Bayesian motion model

- Theory: Optimal solution
  - unknown noise
  - unknown prior
- Perception: Accounts for psychophysical data
  - qualitative
  - deterministic (what about response variability?)
- Physiology: Seems loosely plausible...
  - but mechanism unspecified and non-unique

[Stocker & Simoncelli, Nature Neurosci 06]
Prior/likelihood from psychophysics

- Assume Gaussian likelihood, with contrast-dependent width
- Assume prior is smooth
- Assume MAP estimates (max posterior)
- Speed-matching and speed-discrimination data are sufficient to determine prior and likelihood width

[Stocker & Simoncelli, '06]
Model accounts for perceptual data

- Relative matching speed
  - \( c_1 = 0.5 \)
  - \( c_2 = 0.8 \)
  - \( c_2 = 0.4 \)
  - \( c_2 = 0.2 \)
  - \( c_2 = 0.1 \)
  - \( c_2 = 0.05 \)

- Relative threshold \( \Delta V \)
  - \( c_{1,2} = 0.075 \)

[Stocker & Simoncelli, '06]

Model comparison

- Weibull fit
- Avg probability of data
- Coin-flipping model

[Stocker & Simoncelli, '06]
Prior

Likelihood width

Speed tuning in area MT is approximately constant in log(v)

- Maunsell & Van Essen 83
- also Nover et. al. 05

Area MT contrast-response function:

$$r(c) = \alpha \frac{c^k}{c^k + c_{50}^k} + \beta$$

- Selar et. al. 90
Prior

Likelihood width

**Area MT contrast-response function:**

\[ r(c) = \alpha \frac{c^k}{c^k + c_{50}^k} + \beta \]

- Sclar et al. 90

**Likelihood width under Poisson variability:**

\[ w(c) \propto \left( \frac{1}{r(c)} \right)^2 \]

How is prior implemented?

1. MT encodes likelihood, prior imposed at readout
2. MT encodes posterior (prior is built in)
   - Coverage of speed tuning curves
   - Response gain dependent on tuning speed
3. Some combination of the two
Conclusions

- Bayesian model of local motion
  - fits perceptual speed-matching data
  - prior for speed: power-law
  - likelihood width:
    - constant in log(v)
    - falls with contrast, as predicted by cortical responses
- Should be perceptually validated on other stimuli
- Physiological instantiation/learning of prior
- Encoding/Decoding Cascades