Modeling Visual Acuity in the presence of Fixational Eye Movements

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How can we see so well, even though our eyes are constantly moving?

Our eyes jitter enough to move photoreceptor-tuned features across dozens of cones. How can our mental computations extract these features using only a few spikes from a few neurons, despite the positional uncertainty induced by the random eye movements?

Recurrent Network Architecture

The posterior distribution of the hidden variables can be expressed recursively:

\[ P(\mathbf{s}, \mathbf{x}(n; t)) = \sum_{\mathbf{w}(n; t)} P(\mathbf{w}(n; t)) P(\mathbf{s}, \mathbf{x}(n; t) | \mathbf{w}(n; t)) \]

Convert to differential equation for continuous time dynamics:

\[ P(\mathbf{s}, \mathbf{x}, t) = \frac{d}{dt} P(\mathbf{s}, \mathbf{x}, t) + \mathbf{f}(\mathbf{s}, \mathbf{x}, t) \]

Can construct networks to represent each posterior probability:

Ideal Observer Analysis

Of all decision rules, the Maximum Likelihood (ML) rule gives the minimum error probability:

\[ P_e = \frac{1}{T} \left( \sum_{t=1}^{T} L(t) \right) \]

Error Probability

\[ L(t) = \frac{P(h(t) | s(t))}{P(h(t) | s(t))} \]

Likelihood Ratio

Posterior probabilities depend on average over unknown trajectory:

\[ P(\mathbf{s}, \mathbf{x}(t)) = \sum_{\mathbf{w}(t)} P(\mathbf{w}(t)) P(\mathbf{s}, \mathbf{x}(t) | \mathbf{w}(t)) \]

Key assumptions:

- Conditionally independent retinal responses (Poisson)
- Stimulus moves in a random walk (hidden Markov variable)

Ideal Performance: 2D Network

Assuming the eye is fixed makes small stimuli indistinguishable...

...but moderate misestimates in motion are tolerable

Summary

Fine acuity requires synthesizing information from few retinal spikes along a complex, unknown trajectory.

Brain should use knowledge of eye movement statistics.

Optimal discrimination can be accomplished by a biologically plausible recurrent neural network.

References


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