Modeling the Trial-by-Trial Influence of Fixational Eye Movements on Visual Discrimination

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OVERVIEW

Our research goal is to understand the impact of fixational eye movements on perception. To this end, here we develop a computational model of the effect of fixational eye movements on trial-by-trial neural signals and visual discriminations.

BACKGROUND

Fixational Eye Movements (FEMs)

Characteristics
- Microsaccades: Saccades with amplitudes smaller than 0.5 deg. Typical rate 1-2 times every second.
- Ocular drift: Slow eye movement within the foveal range. Typically < 1 deg/s.

Functions
- Microsaccades: Saccades with amplitudes smaller than 0.5 deg. Typical rate 1-2 times every second.
- Ocular drift: Slow eye movement within the foveal range. Typically < 1 deg/s.
- Spatial selection
- Temporal profile
- Microsaccade
- Ocular drift
- Feature extraction
- Remove statistical redundancy from natural scenes

FUNCTIONS

Oculomotor Strategy for Temporal Coding Visual Space

Ocular drift modulates input signals in a way that depends on the spatial frequency of the stimulus. The same amount of drift yields larger temporal fluctuations at higher spatial frequencies. Higher spatial frequencies lead to broader temporal distributions. (Casile et al. 2019. Elife)

Do FEMs Have Influence on Perception?

It is known that eliminating drift movements selectively impairs sensitivity at high spatial frequencies. To understand the influence of FEMs on perception, a model is needed. The model we built tests the extent to which different eye movement trajectories influence discrimination performance, helps to understand the roles of different classes of LGN neurons in making use of FEM dynamics, and formalizes a link between fixational eye movements, neural activity, and behavioral responses.

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MODEL

Visual Inputs
- Visual pattern: \( I(x, y) = \text{image}(x, y) + \text{noise}(x, y) \)
- Eye positions: \( X(t) \) and \( Y(t) \) (measured at Rucci lab)
- Retinal stimulus: \( S(x, y, t) = \left[ x - X(t), y - Y(t) \right] \ast R(t) \)

Neural Responses at the LGN level

Firing rate of individual cell: linear model followed by rectification

\[ f(x, y, t) = \left( K(x, y) \ast S(x, y, t) \right) \ast R(t) \]

Receptive field model: center and surround each with separable spatial \( (F) \) and temporal \( (G) \) components. (Rucci et al. 2000. J. Neurosci.)

\[ K(x, y, t) = F^c(x, y) G^c(t) + F^s(x, y) G^s(t) \]

Spatial profile \( (F^c, F^s, F) \): 2D circular Gaussian distribution

\[ F(x, y) = Ke^{-\frac{(x^2+y^2)}{2\sigma^2}} \]

Temporal profile \( (G^c, G^s, G) \): a series of low-pass and high-pass stages

\[ G(t) = Ae^{\frac{-t}{\tau}} \]

Decision Model

Single neuron

\[ p(S_i | r) = \frac{p(r | S_i)p(S_i)}{p(r)} \]

Multiple neurons

- We assume neurons are conditionally independent
- Estimate the confusion matrix by evaluating the summation of all cell log likelihood ratios

Main steps:
1. Reduce the dimensionality by principal component analysis (PCA)
2. Identify the optimal linear discriminator by Fisher discriminant
3. The decision is based on maximum posteriori probability (MAP) computed by Bayes rule

RESULTS & NEXT STEPS

Performance of Individual Trajectories

Interim Conclusions
The model predicts trial-by-trial effect of FEM trajectories on performance. The benefit of specific trajectories is predicted to be substantial.

Next Steps
1. Experimental data collection to compare the computational and modeling results
2. Investigate the characteristics of "good" and "bad" trajectories

Performance of individual cells and a population of cells

Interim Conclusions
The model makes predictions about the retinal basis of performance based on (1) number of cells (2) cell types (3) cell locations

Next Step
Simulate with cell hybrids to determine the role of spatial and temporal differences between M and P cells in making use of FEM dynamics

Performance on Different Discrimination Tasks

Interim Conclusions
The benefit of specific trajectories is predicted to be task dependent.

Next Step
Experimental data collection to study whether control of FEMs would enable FEM trajectories to adapt to the visual task.