Theory of visual search for foveated visual systems

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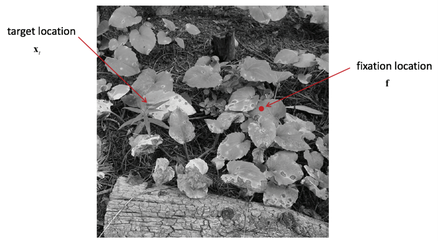
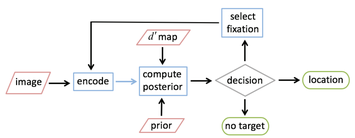
Background and Motivation



Generic Framework



Key Components of Theory

- **Target and background properties** $L(\mathbf{x}), C(\mathbf{x}), S(\mathbf{x}), \|T_\lambda(\mathbf{x})\|$
- **Variation in retinal processing across the visual field** $F(\mathbf{x})$
- **Intrinsic location uncertainty** $U(\mathbf{x})$
- **Covert selection and attenuation** $prior(\mathbf{x}), A(\mathbf{x})$
- **Fixation selection**

Covert Search Theory

$$R(\mathbf{x}) \sim \begin{cases} \mathcal{N}\left[d'(\mathbf{x})\rho_{TT}(\mathbf{x}-\mathbf{x}_T), 1\right] & \text{present} \\ \mathcal{N}[0,1] & \text{absent} \end{cases}$$ *Normalized template response map*

$$d'(\mathbf{x}) \propto \left[a\frac{\|T_\lambda(\mathbf{x})\|}{L(\mathbf{x})C(\mathbf{x})S(\mathbf{x})}F(\mathbf{x})\right]^\beta$$ *Detectability map without uncertainty*

$$l(\mathbf{x}) = d'(\mathbf{x})R(\mathbf{x}) - 0.5d'^2(\mathbf{x})$$ *Log-likelihood ratio map*

$$\max_{\mathbf{x}}[l(\mathbf{x}) + \ln \text{prior}(\mathbf{x}|U(\mathbf{x}))] > \gamma(\mathbf{x})$$ *Target present/absent decision rule*

$$\hat{\mathbf{x}} = \arg\max_{\mathbf{x}}[l(\mathbf{x}) + \ln \text{prior}(\mathbf{x}|U(\mathbf{x}))]$$ *Target location, if present*

$$U(\mathbf{x})$$ *Uncertainty*

White Noise Case

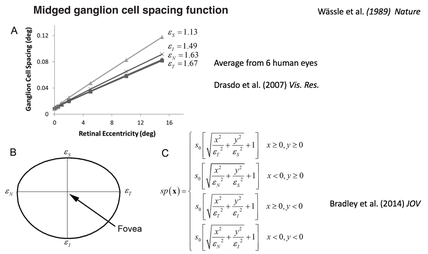
$$d'(\mathbf{x}) \propto \left[\frac{a}{\sigma}F(\mathbf{x})\right]^\beta$$

$$\text{prior}(\mathbf{x}|U(\mathbf{x}))$$

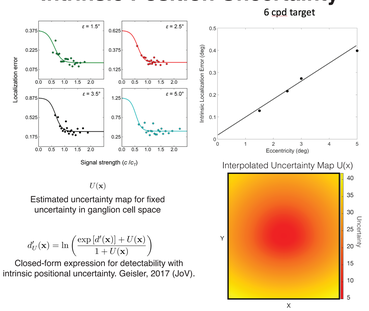
$$U(\mathbf{x})$$

Major factors limiting target detection and search

Ganglion Cell Spacing



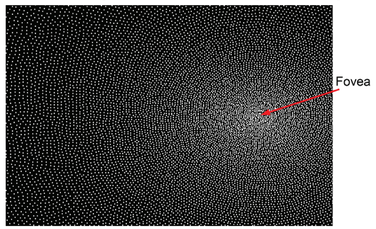
Intrinsic Position Uncertainty



$$d'_U(\mathbf{x}) = \ln\left(\frac{\exp\left[d'(\mathbf{x})\right] + U(\mathbf{x})}{1 + U(\mathbf{x})}\right)$$

Closed-form expression for detectability with intrinsic positional uncertainty. Geisler, 2017 (JoV).

Detectability Falls Inversely with Spacing



Foveation Factor

$$F(\mathbf{x}) = k_0\frac{1 + k_{sp}sp_{pix}(0)}{1 + k_{sp}sp_{pix}(\mathbf{x})}$$

k_{sp} Target dependent constant

Rovamo et al. (1978) *Nature*
Bradley et al. (2014) *JOV*

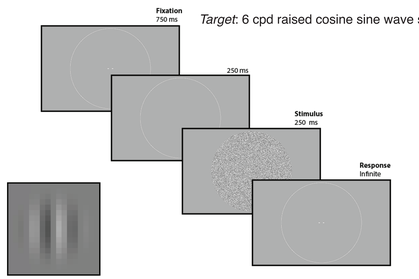
Estimate Remaining Unknowns from Psychophysics

$$d'_U(\mathbf{x}) = \ln\left(\frac{\exp\left[d'(\mathbf{x})\right] + U(\mathbf{x})}{1 + U(\mathbf{x})}\right)$$

$$d'(\mathbf{x}) = [a(\mathbf{x})F(x)]^\beta$$

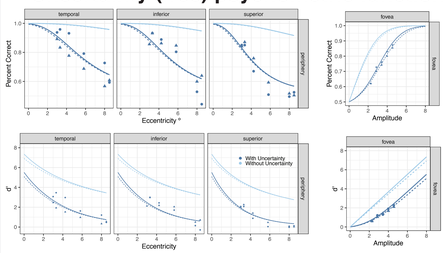
$$F(\mathbf{x}) = k_0\frac{1 + k_{sp}sp_{pix}(0)}{1 + k_{sp}sp_{pix}(\mathbf{x})}$$

Detection and Search Tasks



Target: 6 cpd raised cosine sine wave stimulus.

Uncertainty (free) psychometric functions



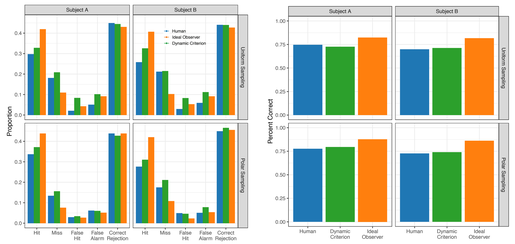
$k_0 = (.87, .92)$ $k_{sp} = (.25, .28)$

Measure detectability across the visual field using a psychophysical task

Estimated parameters are used to interpolate an uncertainty-free detectability map

Results

Task Performance



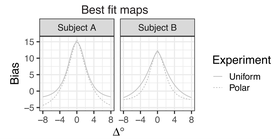
Dynamic Criterion

Add bias term to the optimal criterion

$$\max_{\mathbf{x}}[l(\mathbf{x}) + \ln \text{prior}(\mathbf{x}|U(\mathbf{x}))] > \gamma_{opt}(x) + \hat{\gamma}(x)$$

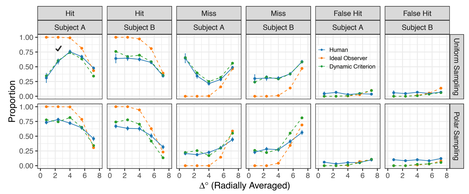
Estimate bias maps via maximum likelihood

$$\text{argmax } Pr\left(\mathcal{D}|\hat{\gamma}_\theta(x)\right)$$

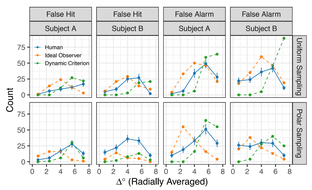


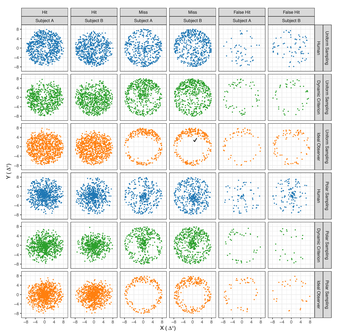
Spatial Distribution of Responses

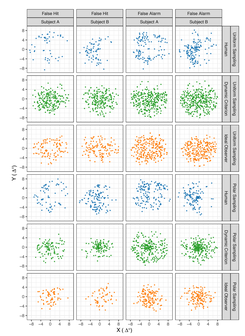
By Target Location



By Pointing Location







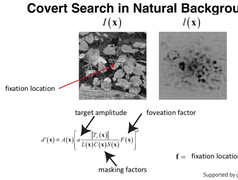
Future Directions and Conclusions

Multiple Fixation Search

Covert Search Model + Fixation Selection

- Uncertainty-limited ideal covert search approximates human performance
- Humans have spatial biases in responses that clearly deviate from the ideal
- A spatially varying criterion can explain the search biases

Covert Search in Natural Backgrounds



Supported by grant EY11747