Ocular drift: modulating retinal power and interactions with retinal sensitivity

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Questions and Overview

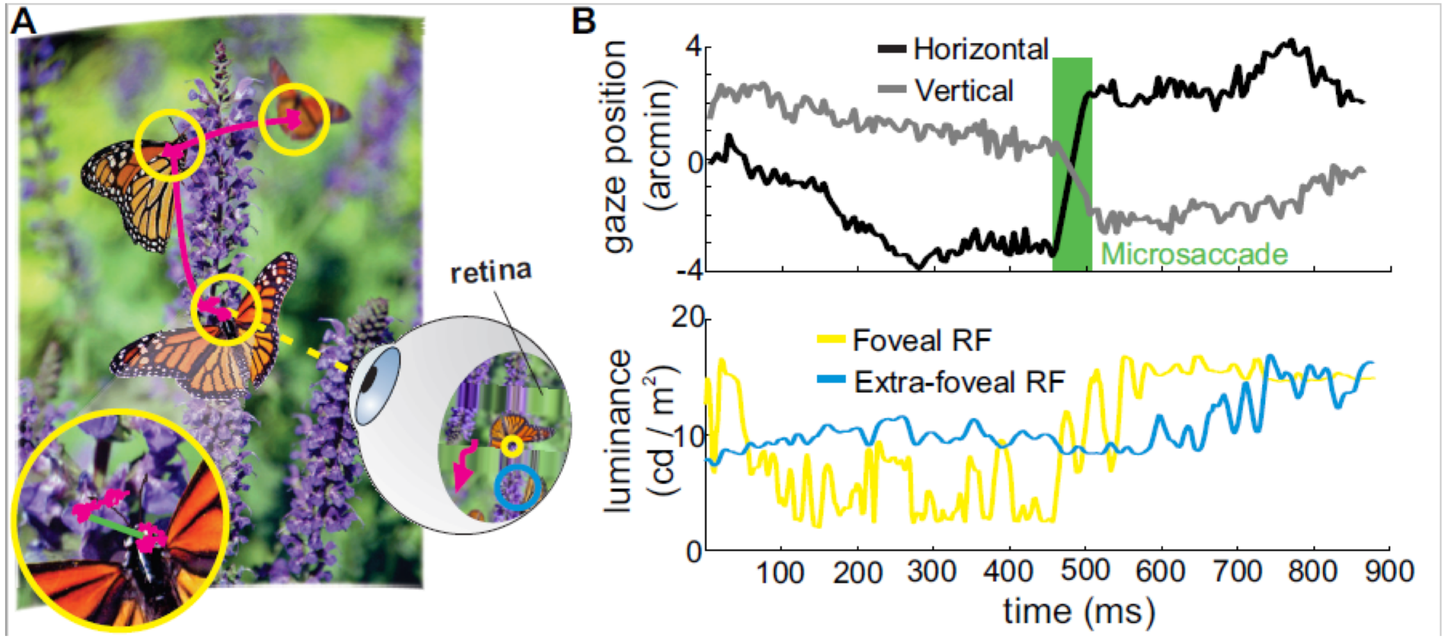
- How does drift contribute to vision across the retina?
- How much drift is optimal?
- Is drift controlled to modulate temporal power on the retina?

- Background
- Methods for studying perceptual and computational consequences of drift
- Current state of the “Drift Gain” projects
- **Next Steps**

Background

What is ocular drift?

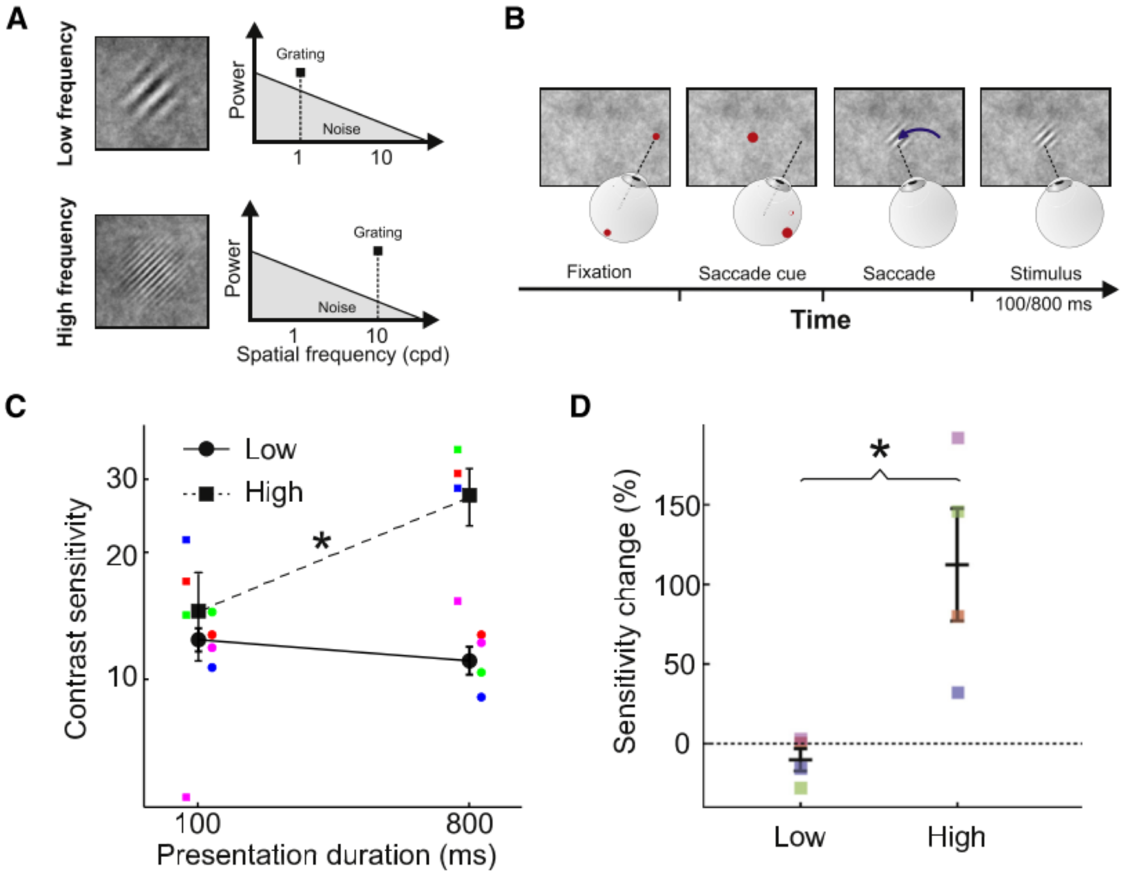
- Wandering motion of the eye between saccadic events
- In the fovea, drift can move the image on the retina by many photoreceptors
- “slow-control”

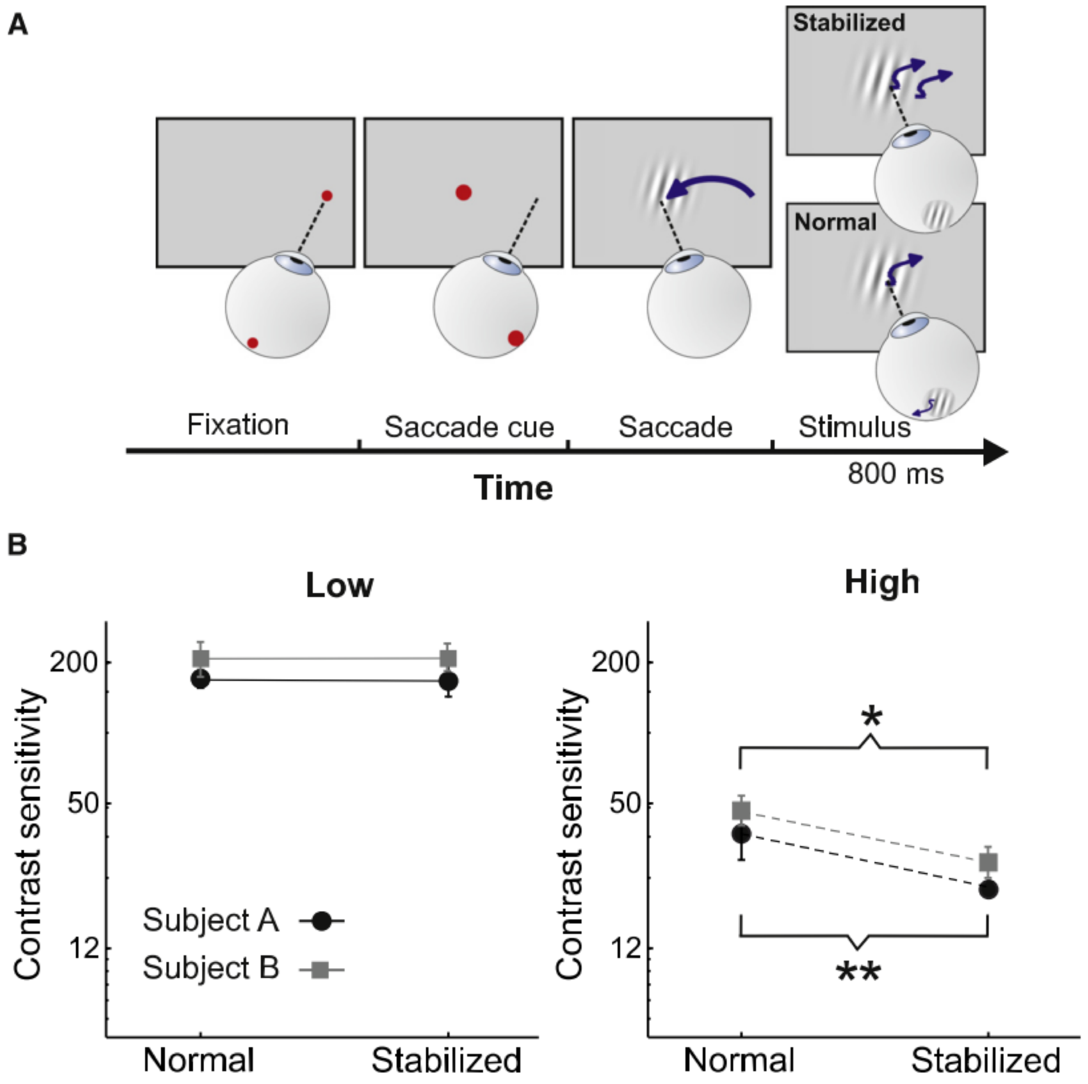


Why do we drift?

- Drive responses from retinal ganglion cells (RGC) which prefer dynamic inputs over static
- Space-time transformation to enhance and improve signal-to-noise ratio (SNR) for high spatial frequencies

Why do we drift?



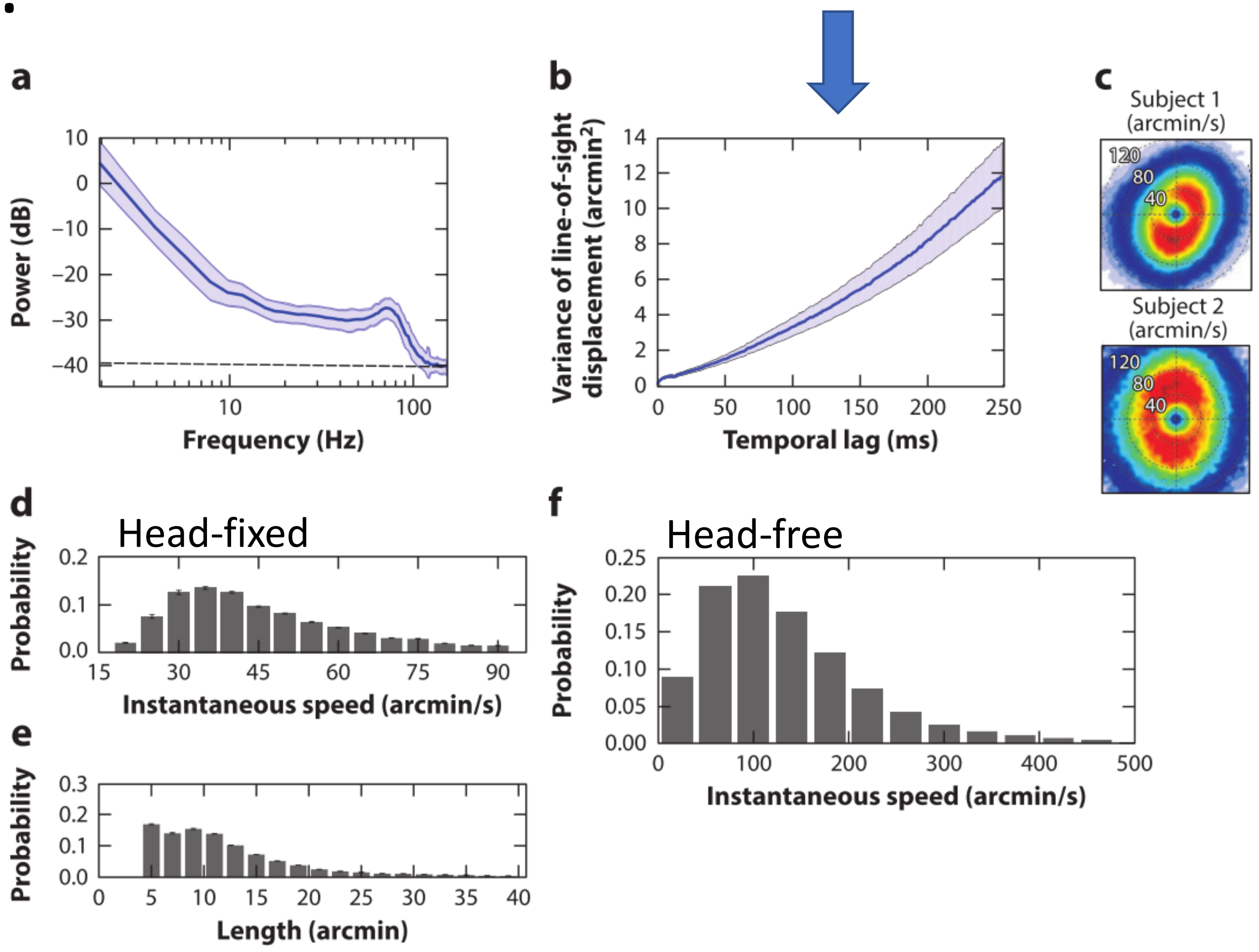


Boi et al 2017

How do we drift?

- Drift during fixation have been well characterized (Cherici et al 2012)
- Maintain velocity of retinal image (Epelboim & Kowler, 1993)
- Characteristics of fixational drift change based on instruction, type of fixation marker, rotation of eye in head, … (Nachmias 1961, Steinman 1973, Kowler 2011)

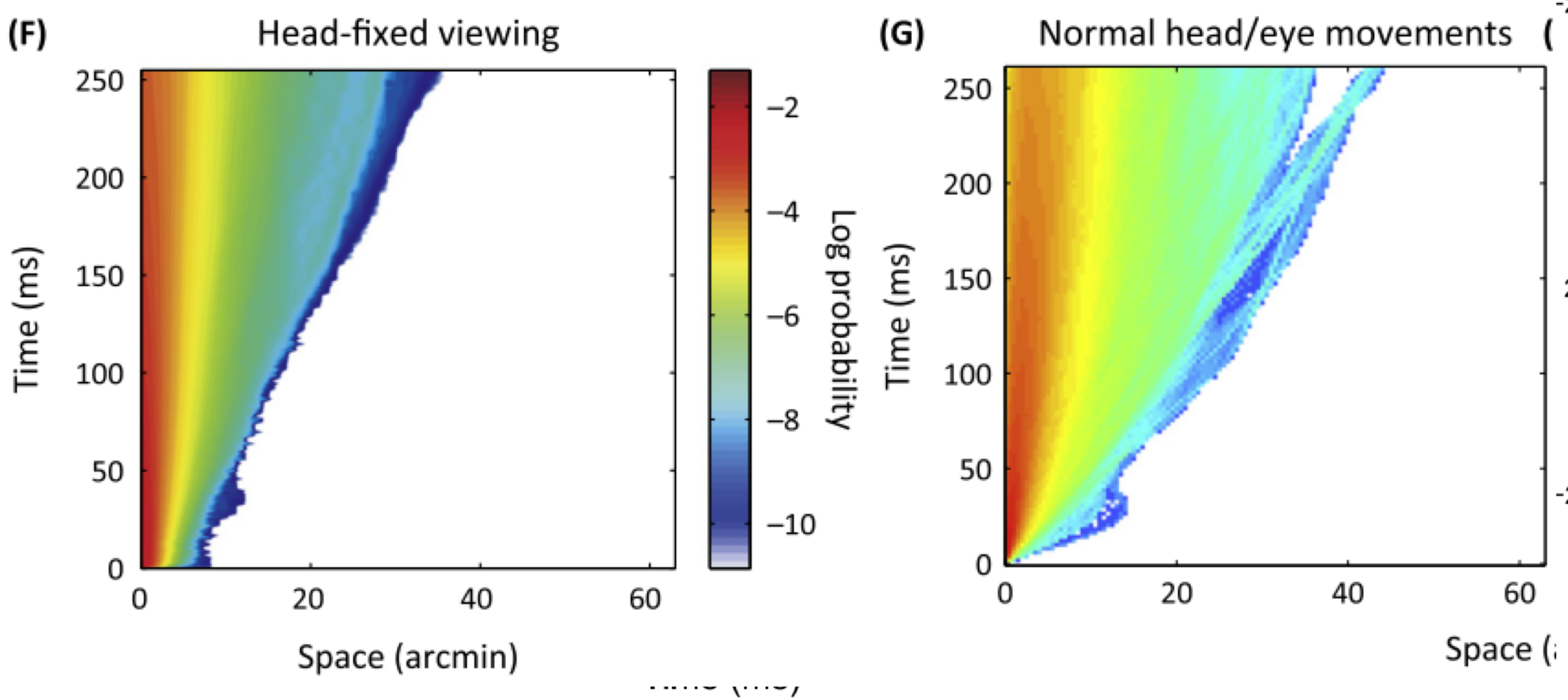
Resembles Brownian motion



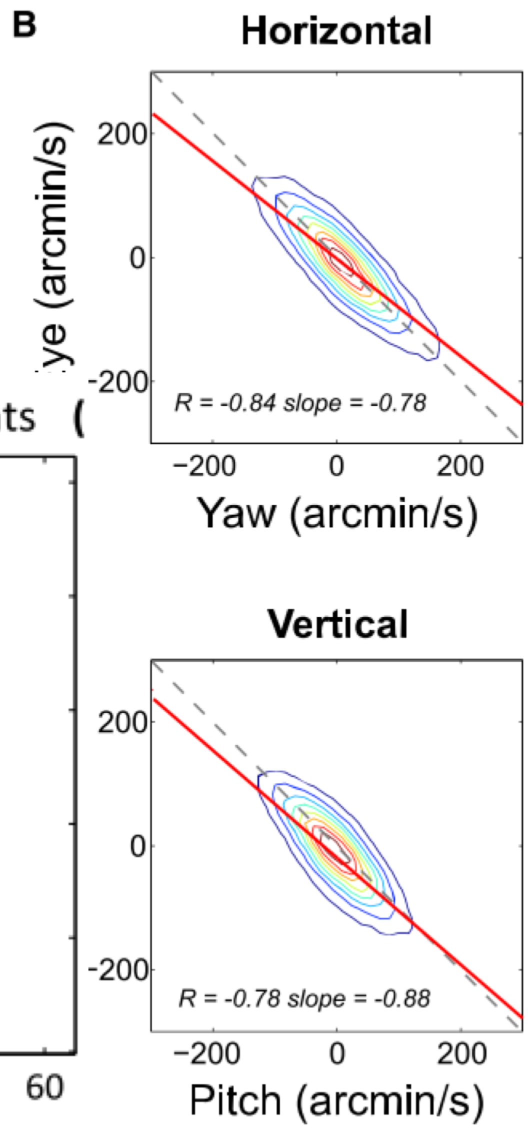
Rucci & Poletti 2015

How do we drift?

During head-free fixation, drifts of the eye and head counterbalance each other so as to maintain the characteristics of retinal image motion observed during head-fixed fixation



Rucci & Victor 2015



Poletti et al 2015

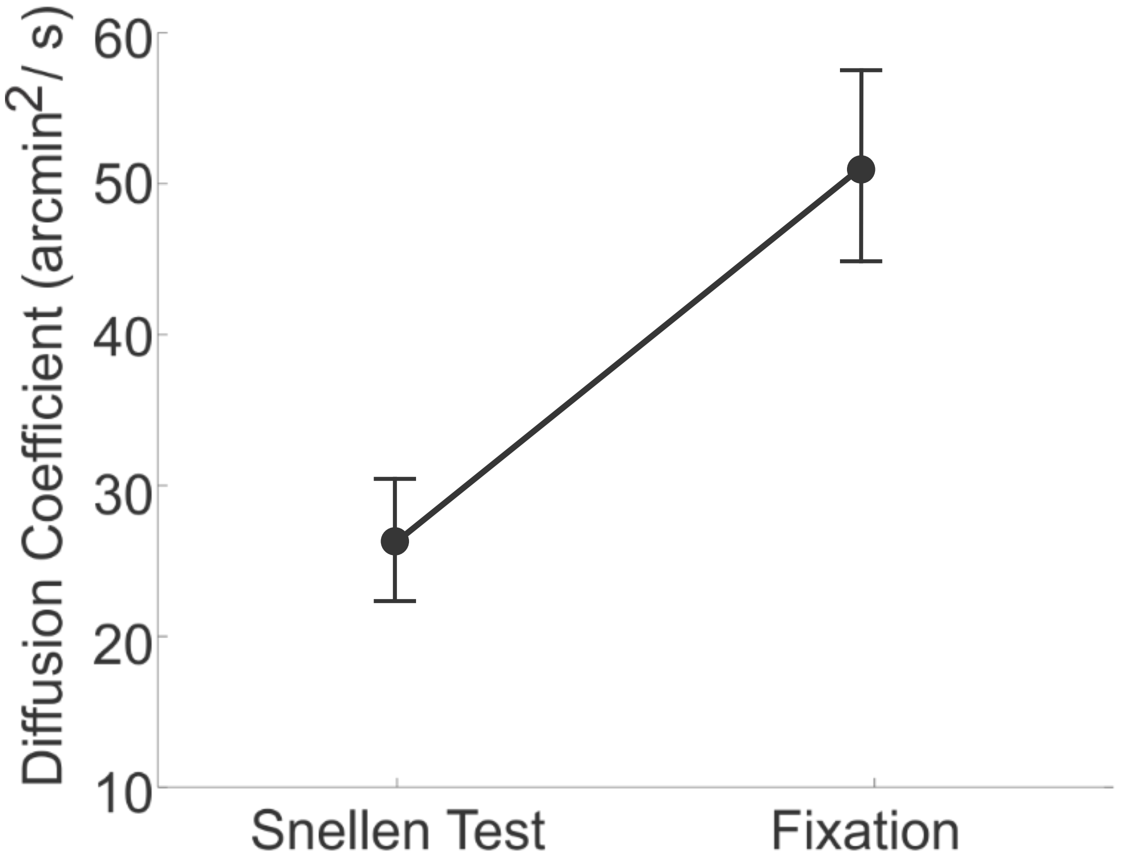
How do we drift?

Probability of gaze displacement over time

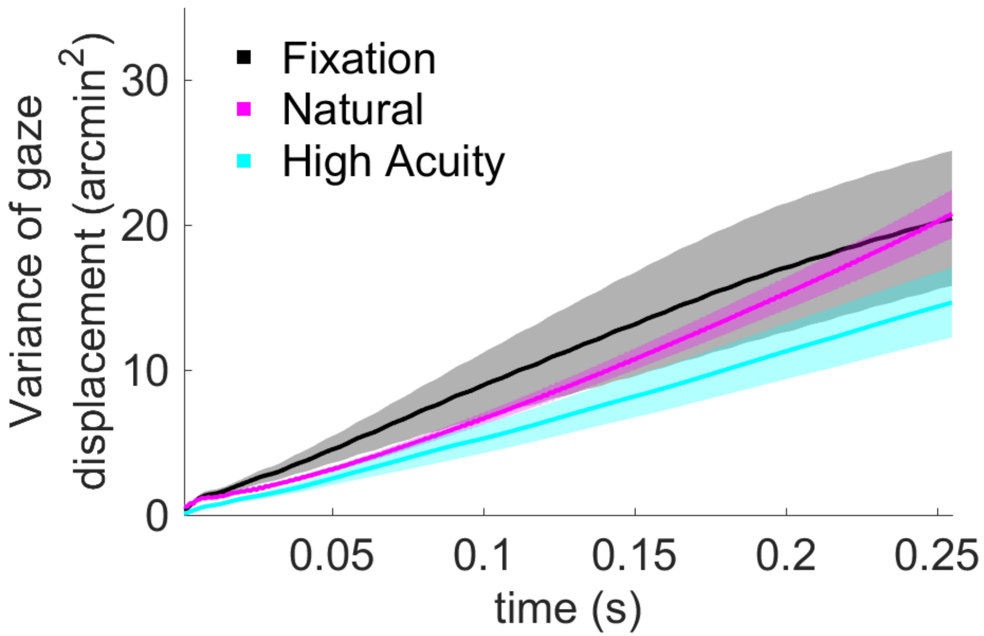
smaller larger

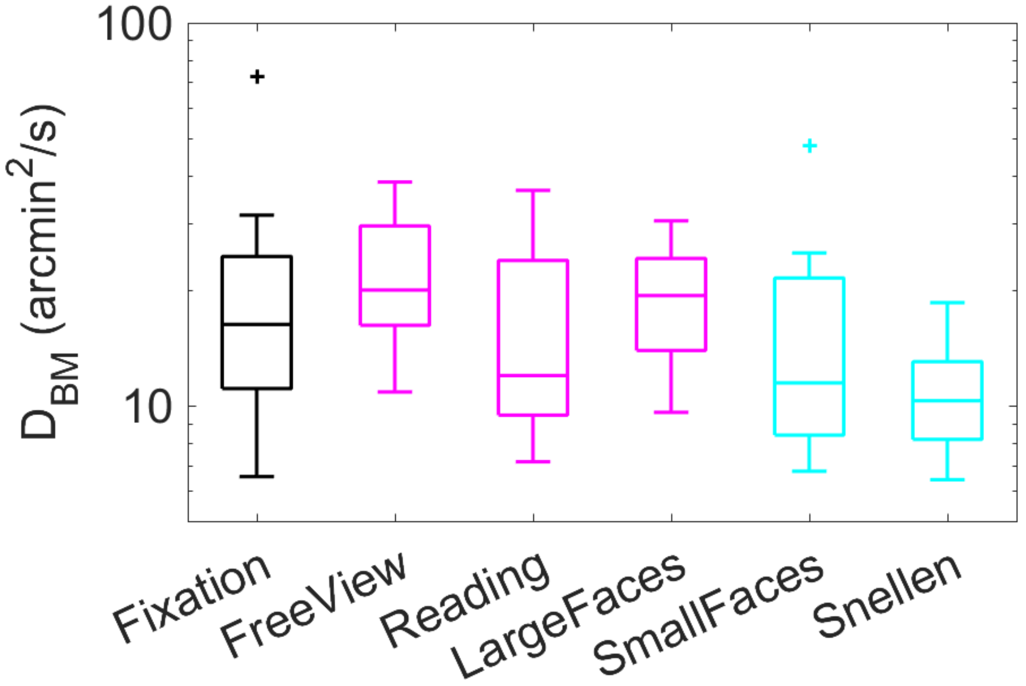
Diffusion Constant

Drift Diffusion Constant



How do we drift?

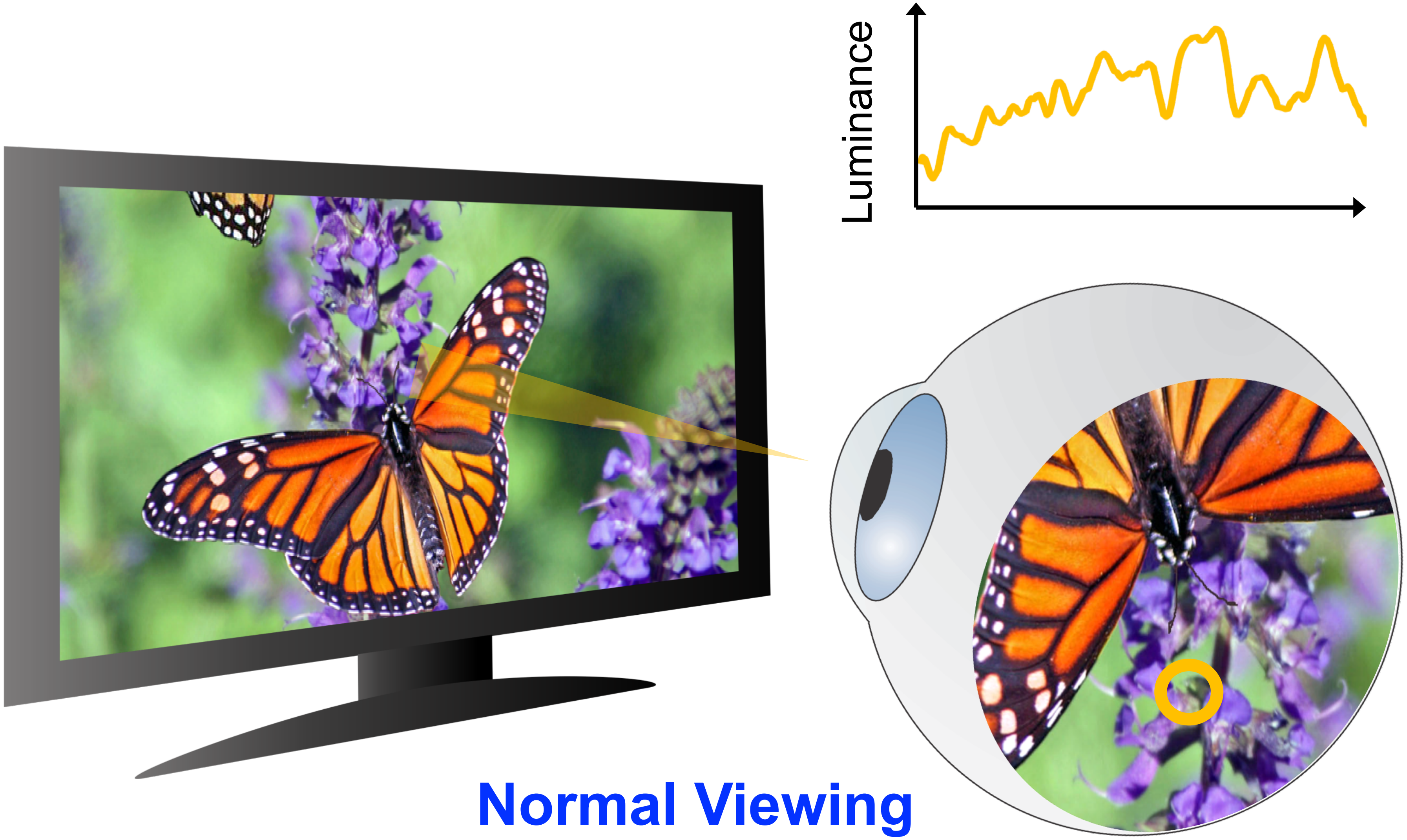




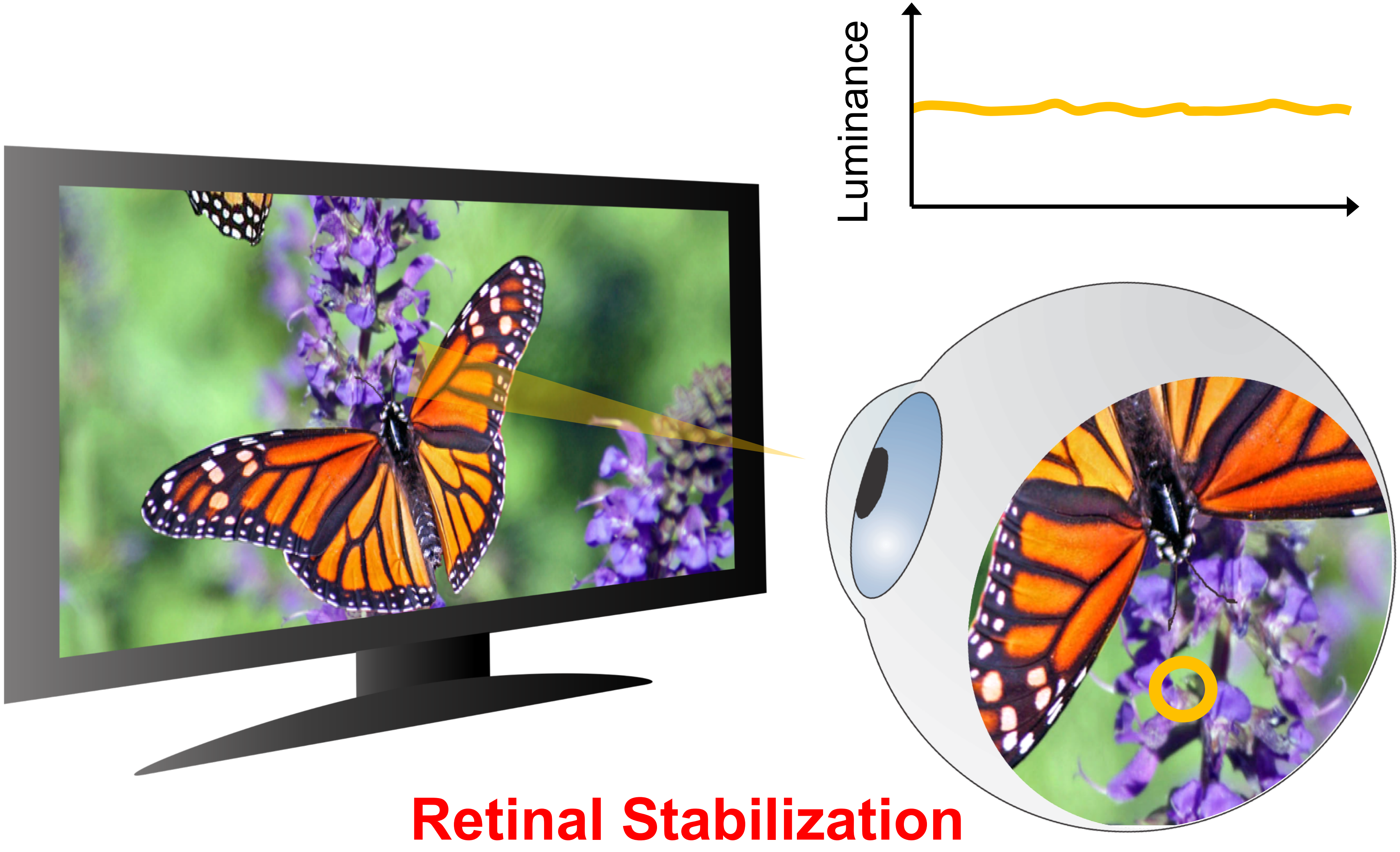
Subject counts: 9, 8, 14, 12, 10, 8

Methods

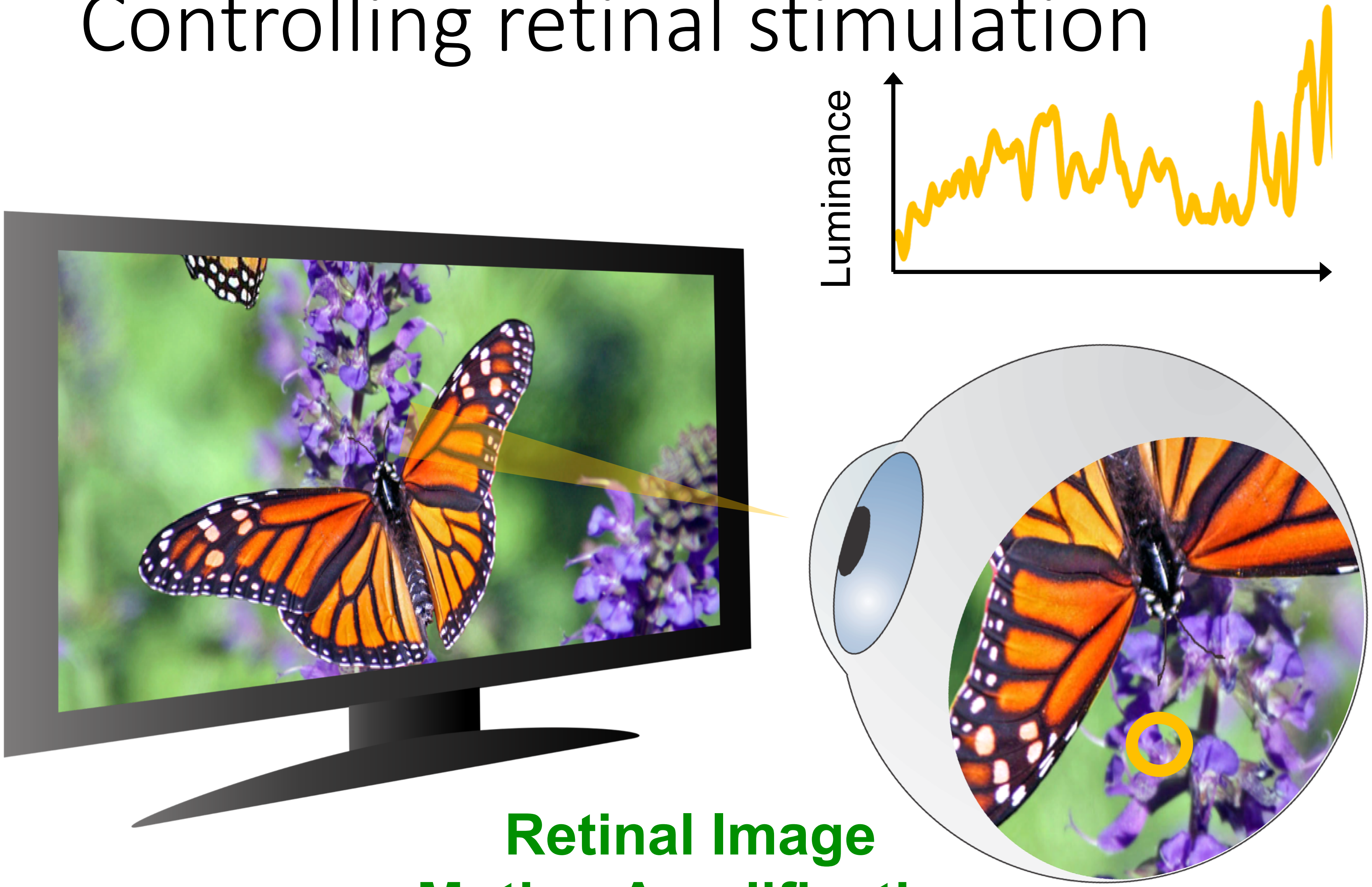
Controlling retinal stimulation



Controlling retinal stimulation

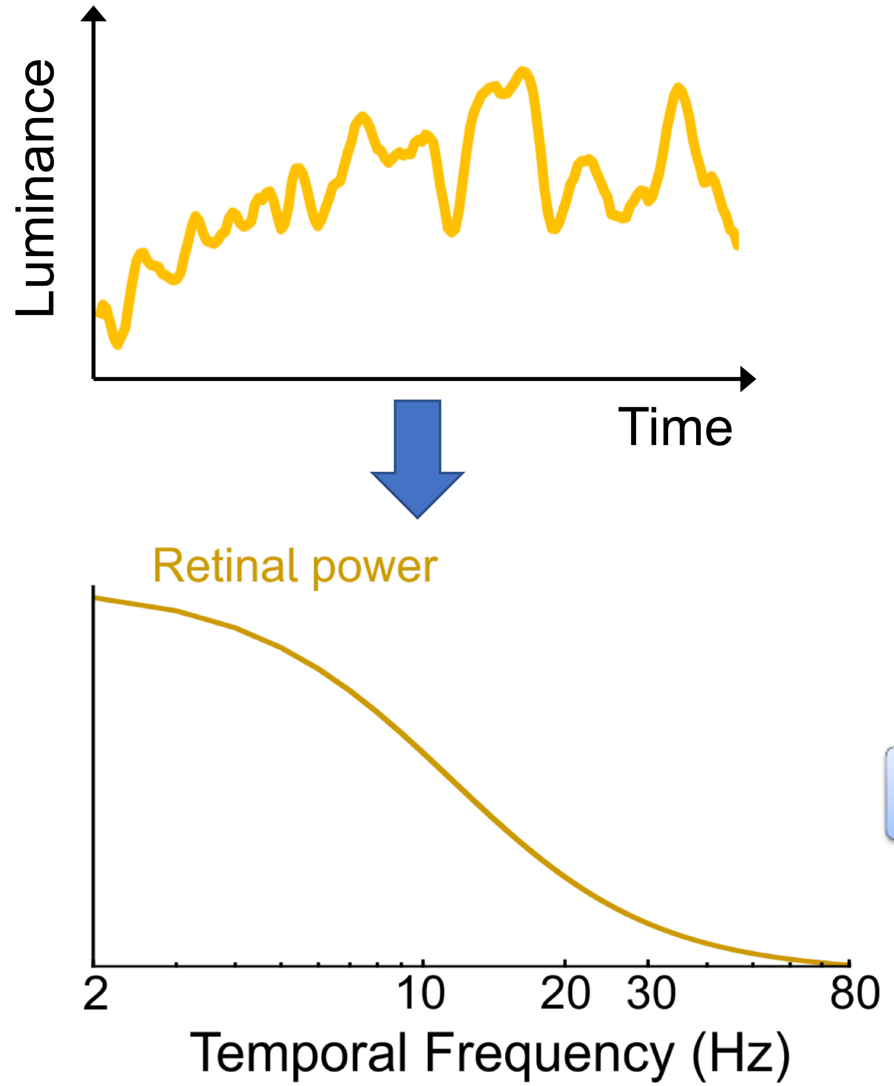


Controlling retinal stimulation

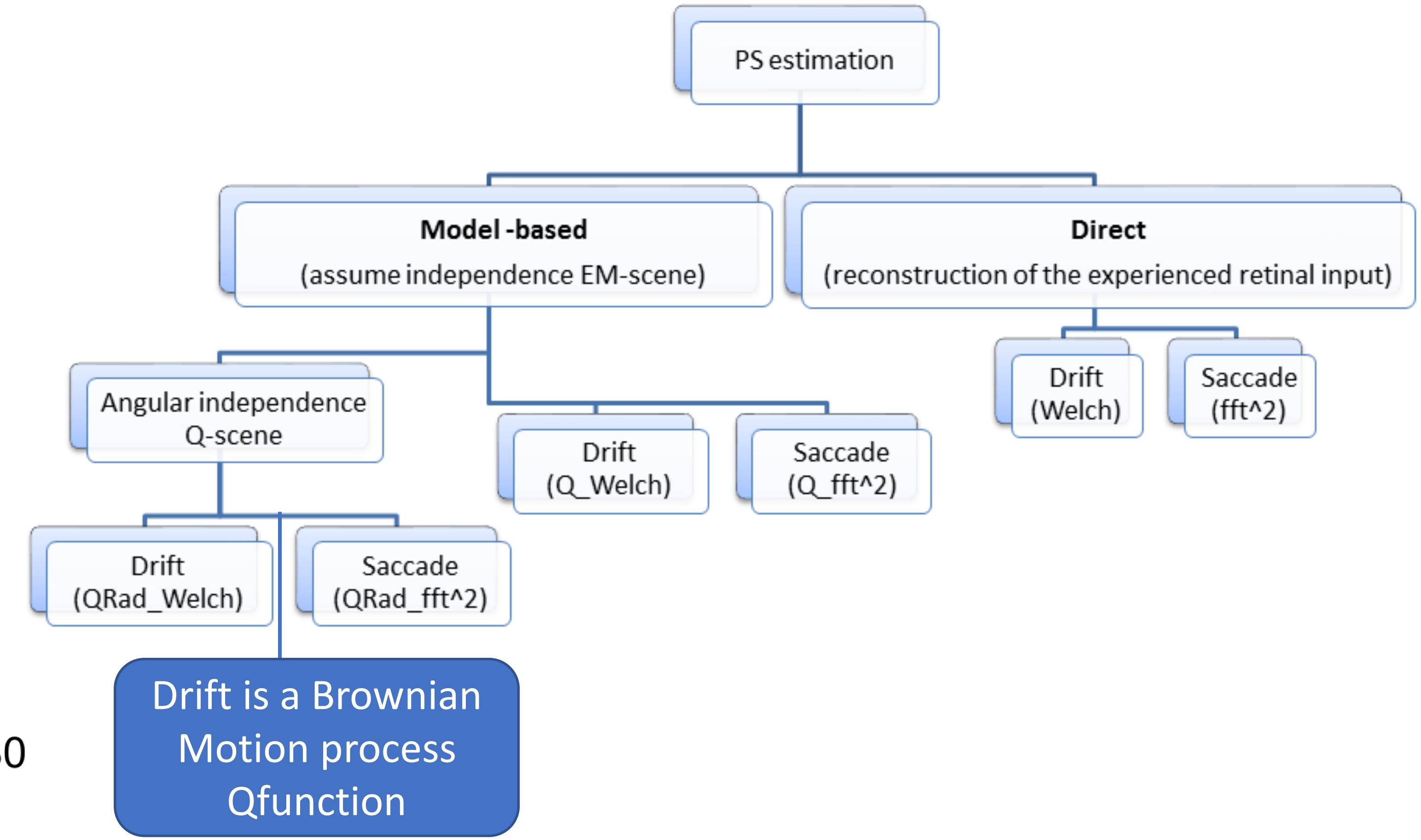


Retinal Image Motion Amplification

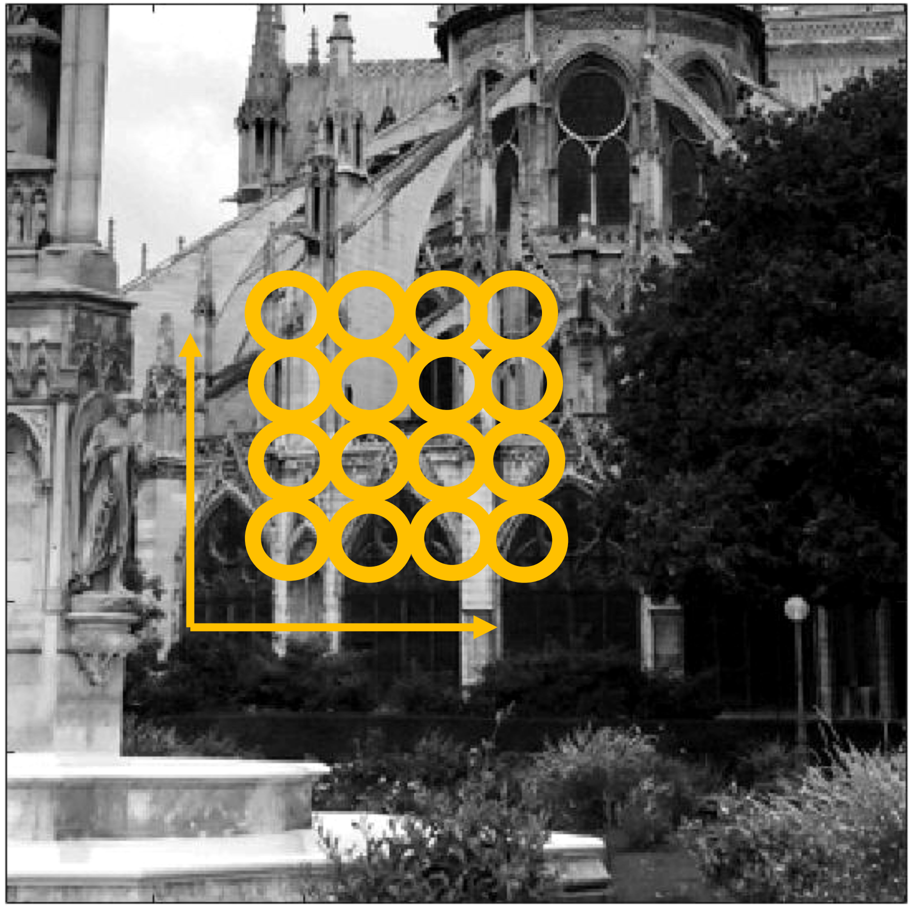
Temporal power on the retina



Power Spectrum estimation



Power Spectrum estimation (Direct)



Stationary image: $i(x, y)$
Eye movements: $\xi_x(t), \xi_y(t)$
Retinal input:

$$r(x, y, t) = i\left(x + \xi_x(t), y + \xi_y(t)\right)$$

PS of retinal input:

$$S\left(k_x, k_y, f\right) = \mathcal{F}\{r(x, y, t)\}^2$$

Power Spectrum estimation (Model-based)

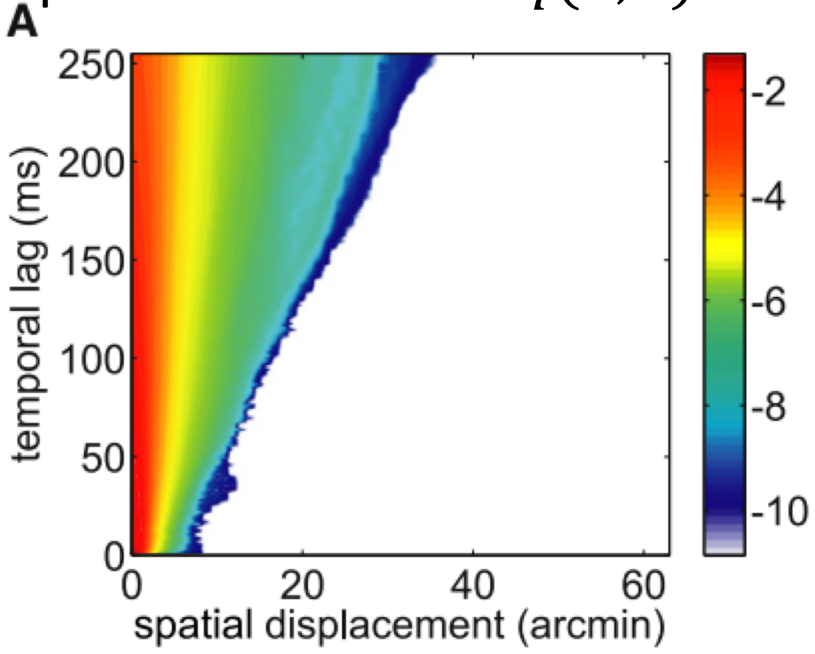
Assumes 1. homogeneity of image and 2. independence of FEM and image

Stationary image: $I(k) = \mathcal{F}\{i(x)\}$
Eye movements: $Q(k, f) = \mathcal{F}\{q(x, \tau)\}$
$q(x, \tau)$: Probability of eye displacement over time

PS of retinal input:

$$S(k, f) = I(k)Q(k, f)$$

1. Empirical estimate of $q(x, \tau)$

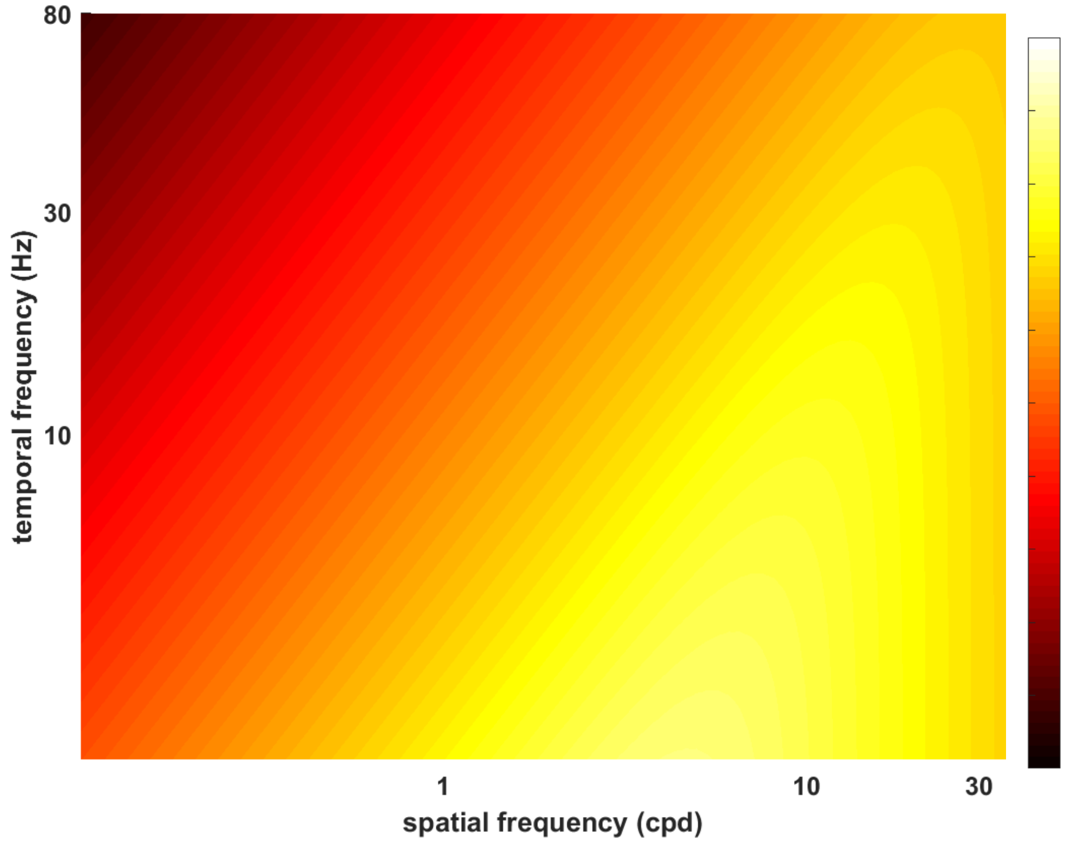


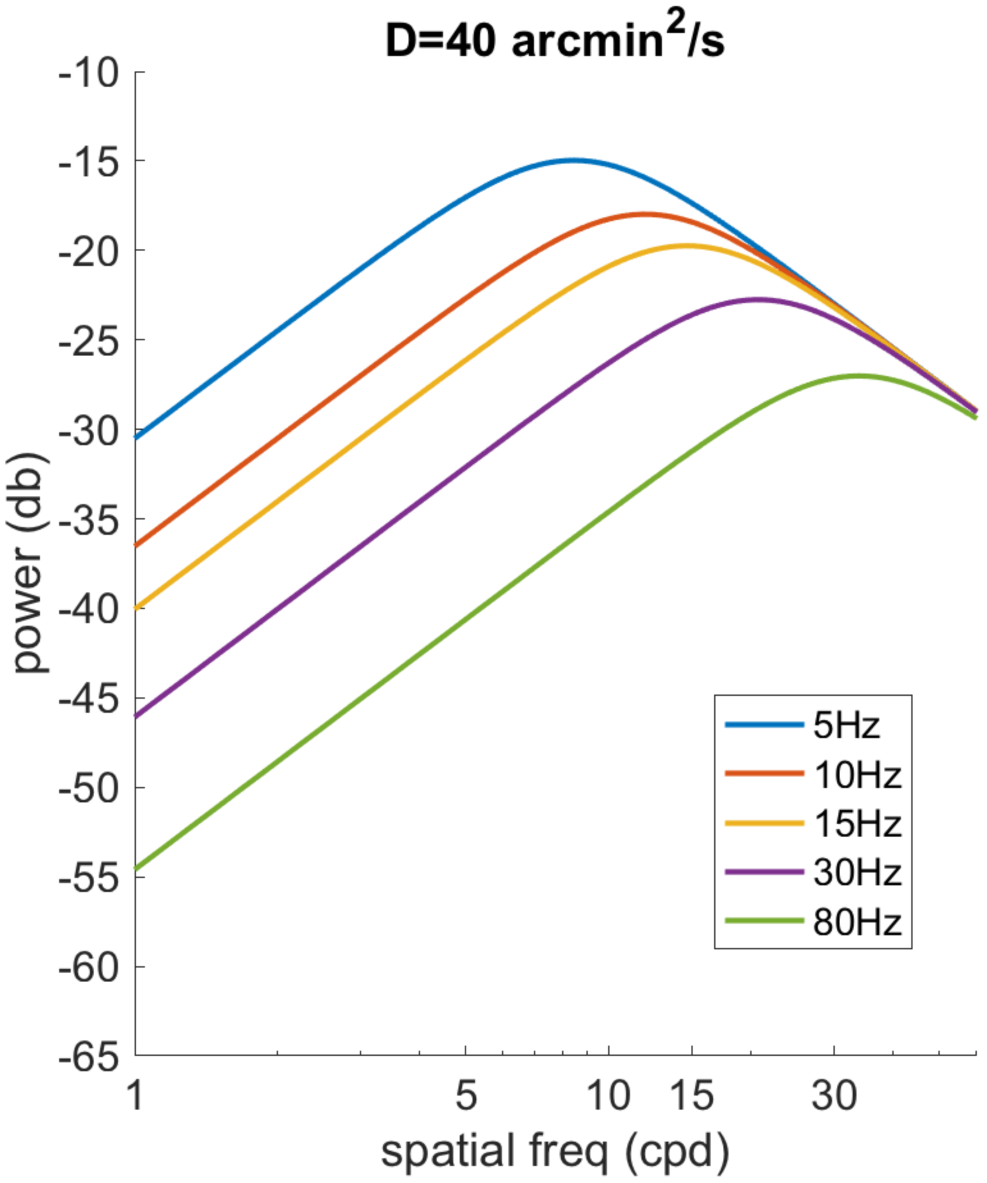
2. Brownian Motion model of $q(x, \tau)$ → known closed forms of $q(x, \tau; D)$ and $Q(k, f; D)$

Kuang et al 2012

Power Spectra

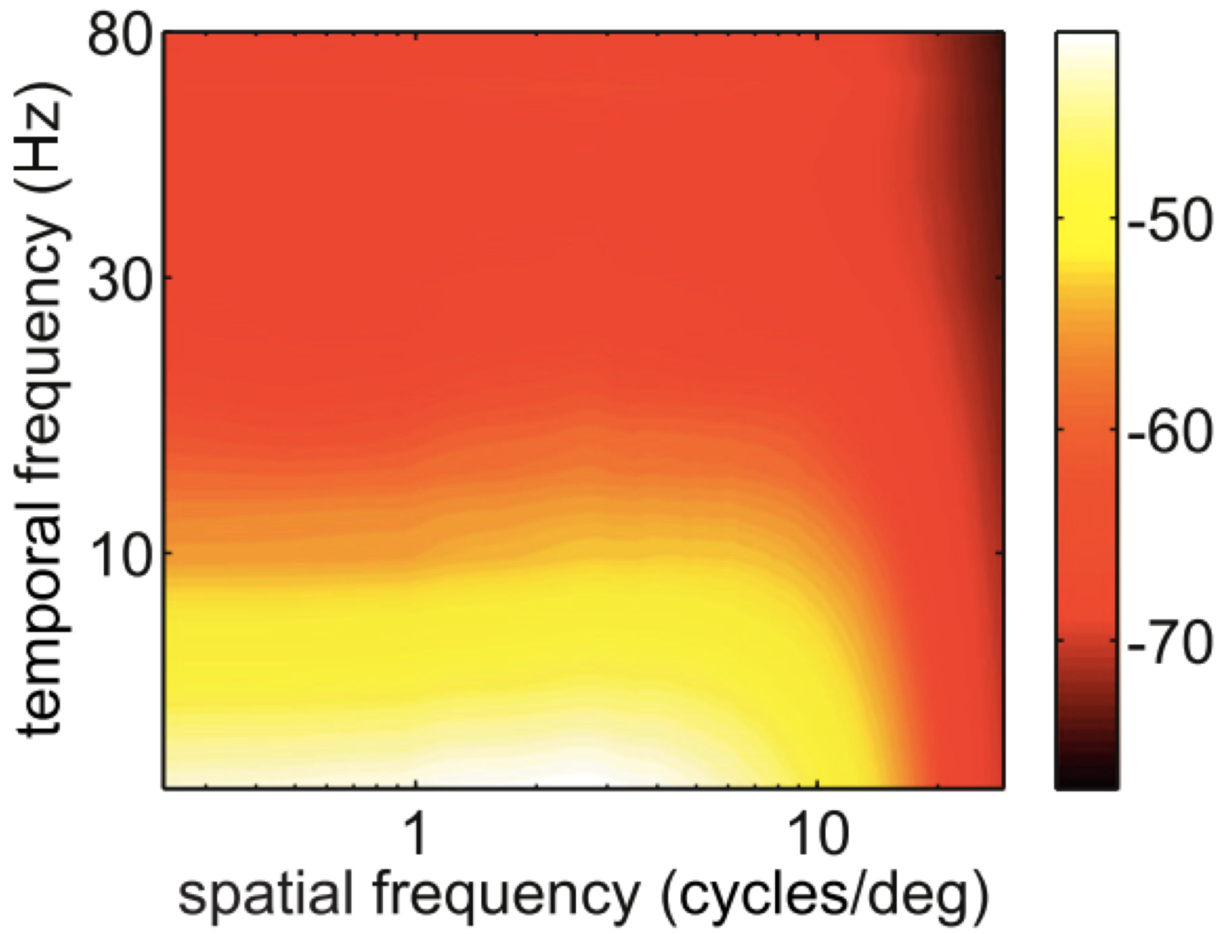
$$Q(k, f; D = 40)$$

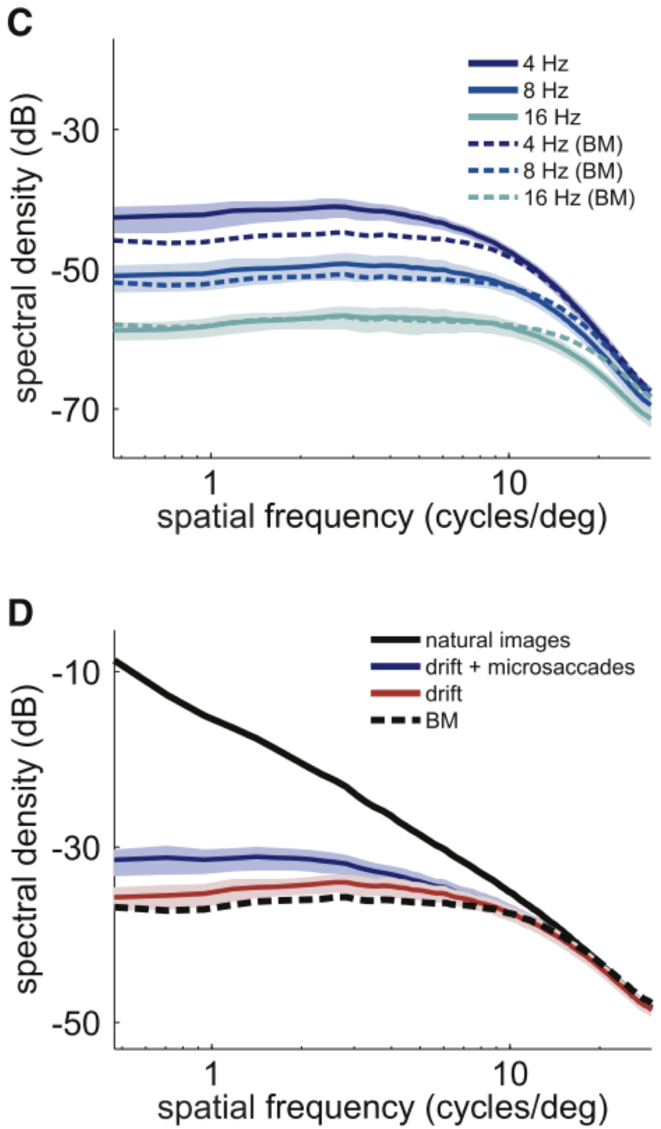




Power Spectra

$S(k, f)$ for natural images

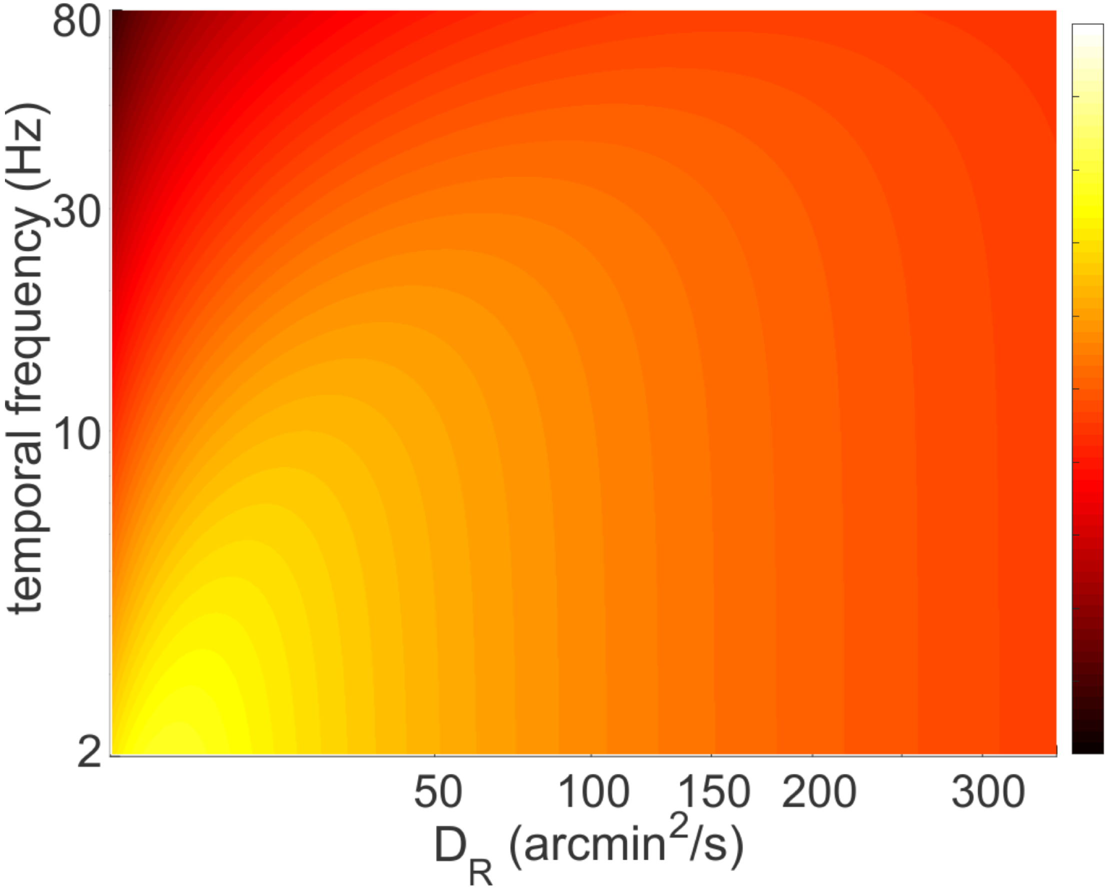




Kuang et al 2012

Power Spectra of BM

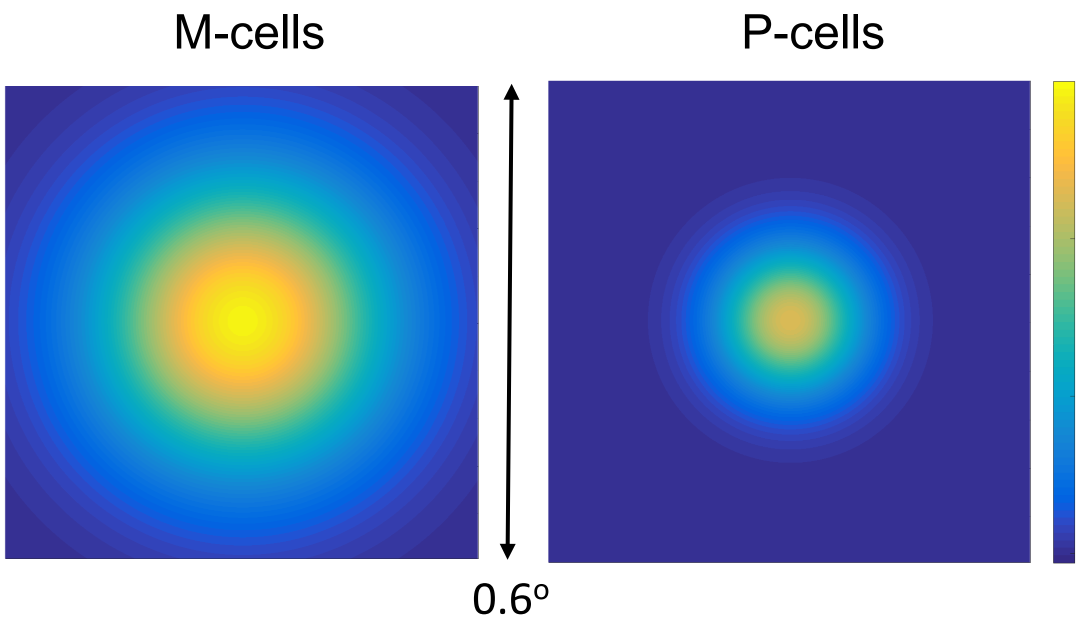
$$Q(k = 16, f; D)$$



RGC Sensitivity

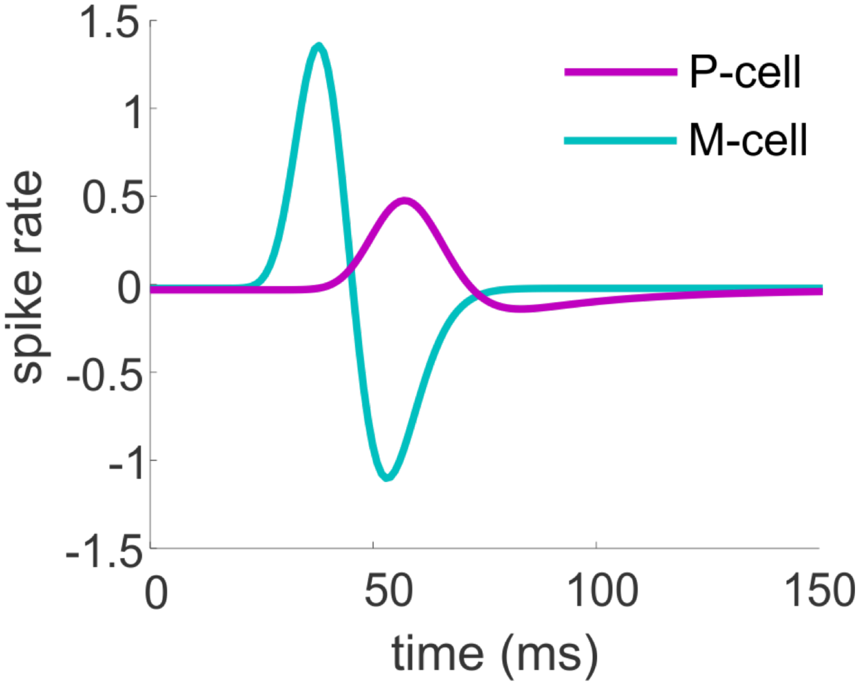
- Neurophysiological measurements of RGC spatiotemporal sensitivity

Spatial Filters



5° eccentricity (Croner & Kaplan, 1995)

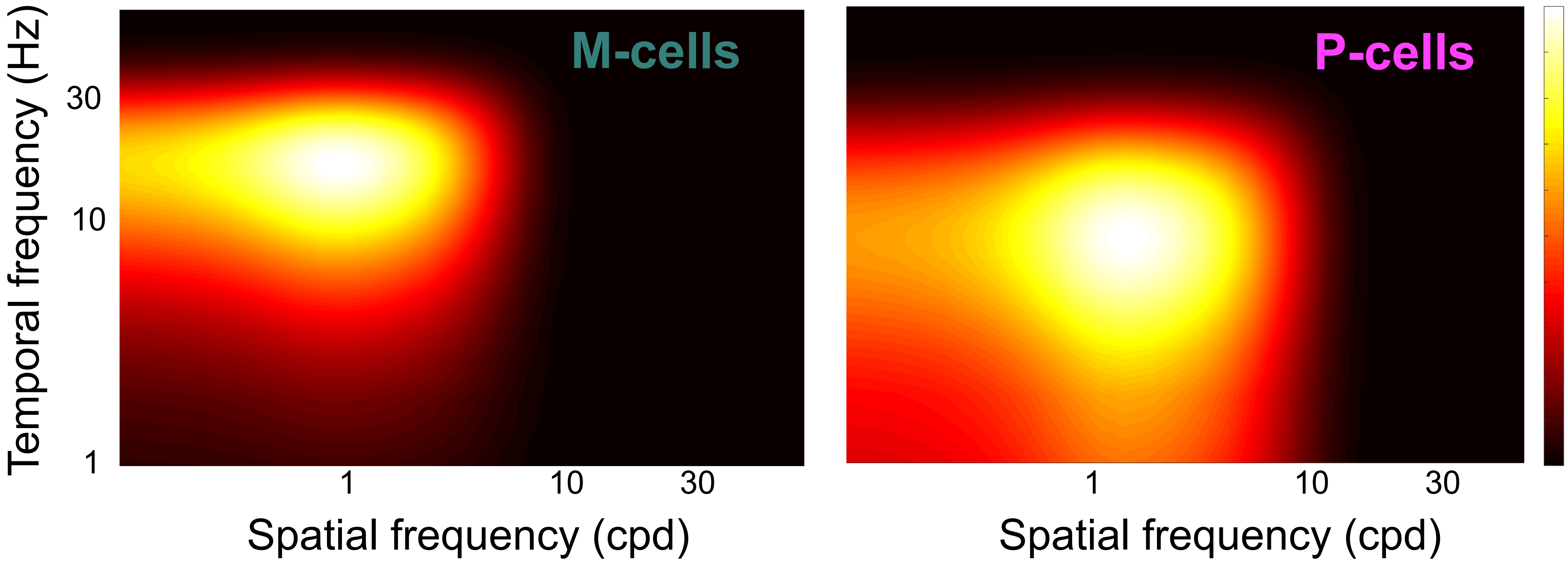
Temporal Filters



2.5° eccentricity (Kaplan & Benardete, 1999ab)

RGC Sensitivity

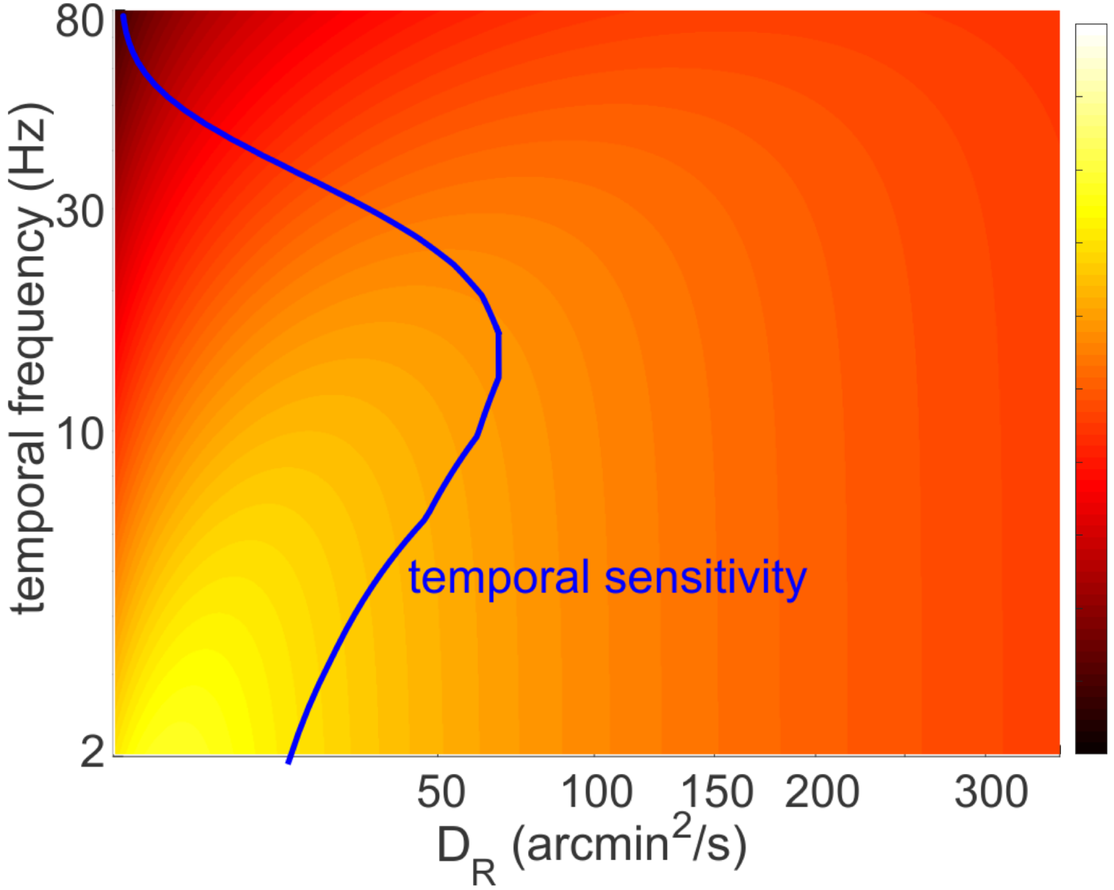
- Neurophysiological measurements of RGC spatiotemporal sensitivity

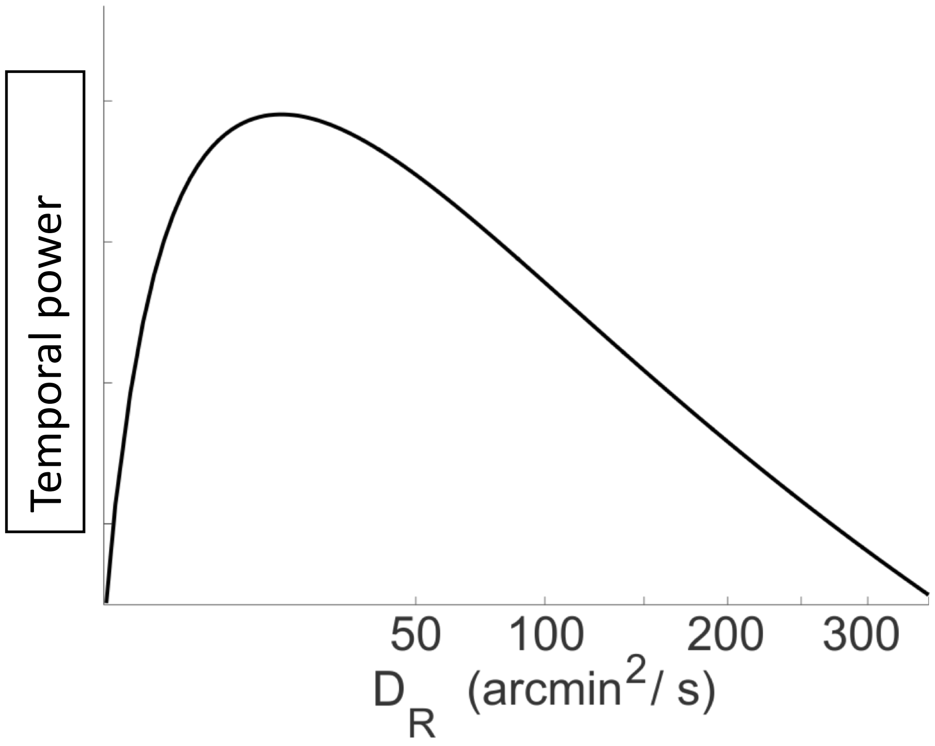


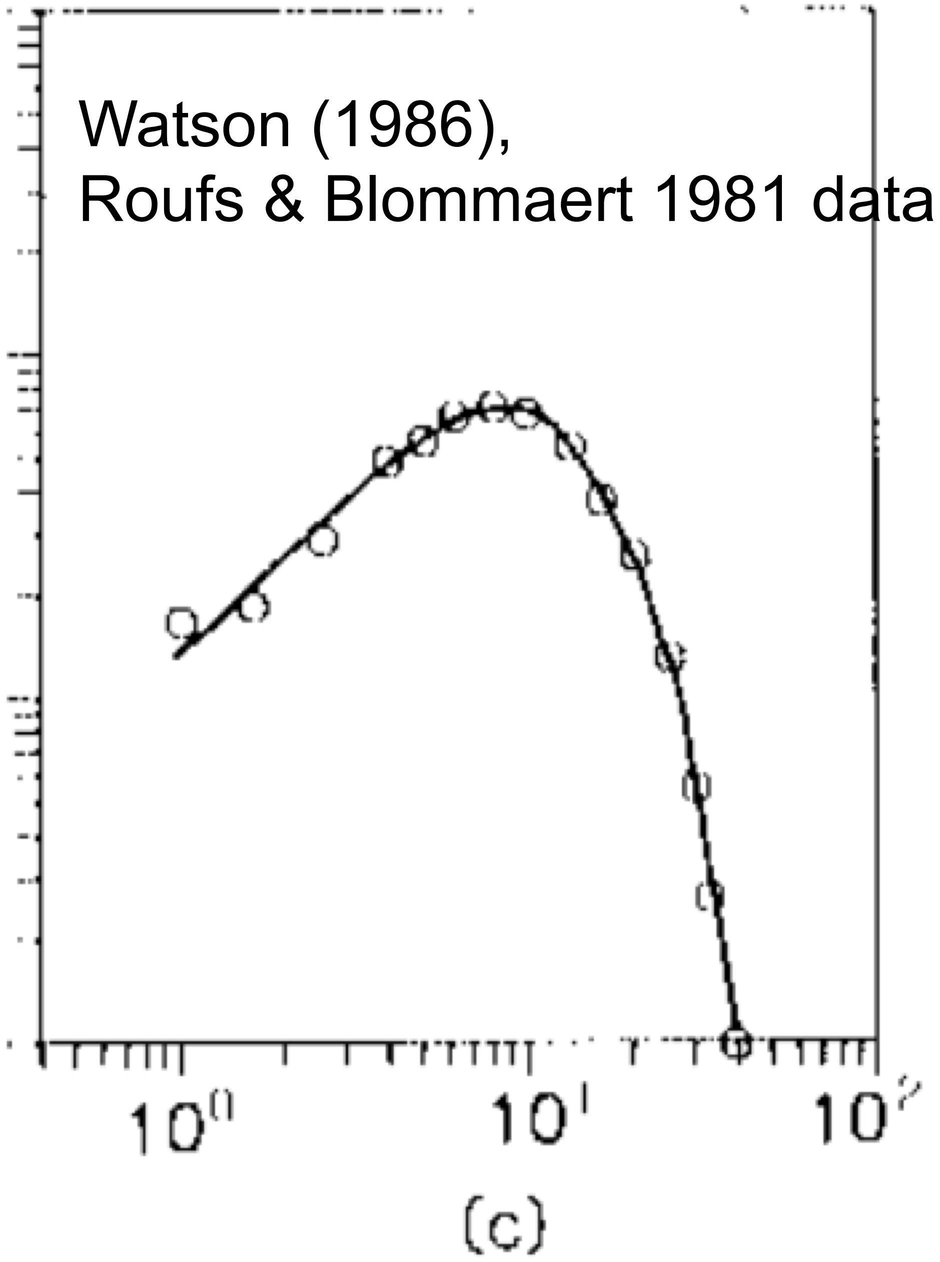
Power Spectra of BM

Retinal Power

$$Q(k = 16, f; D)$$







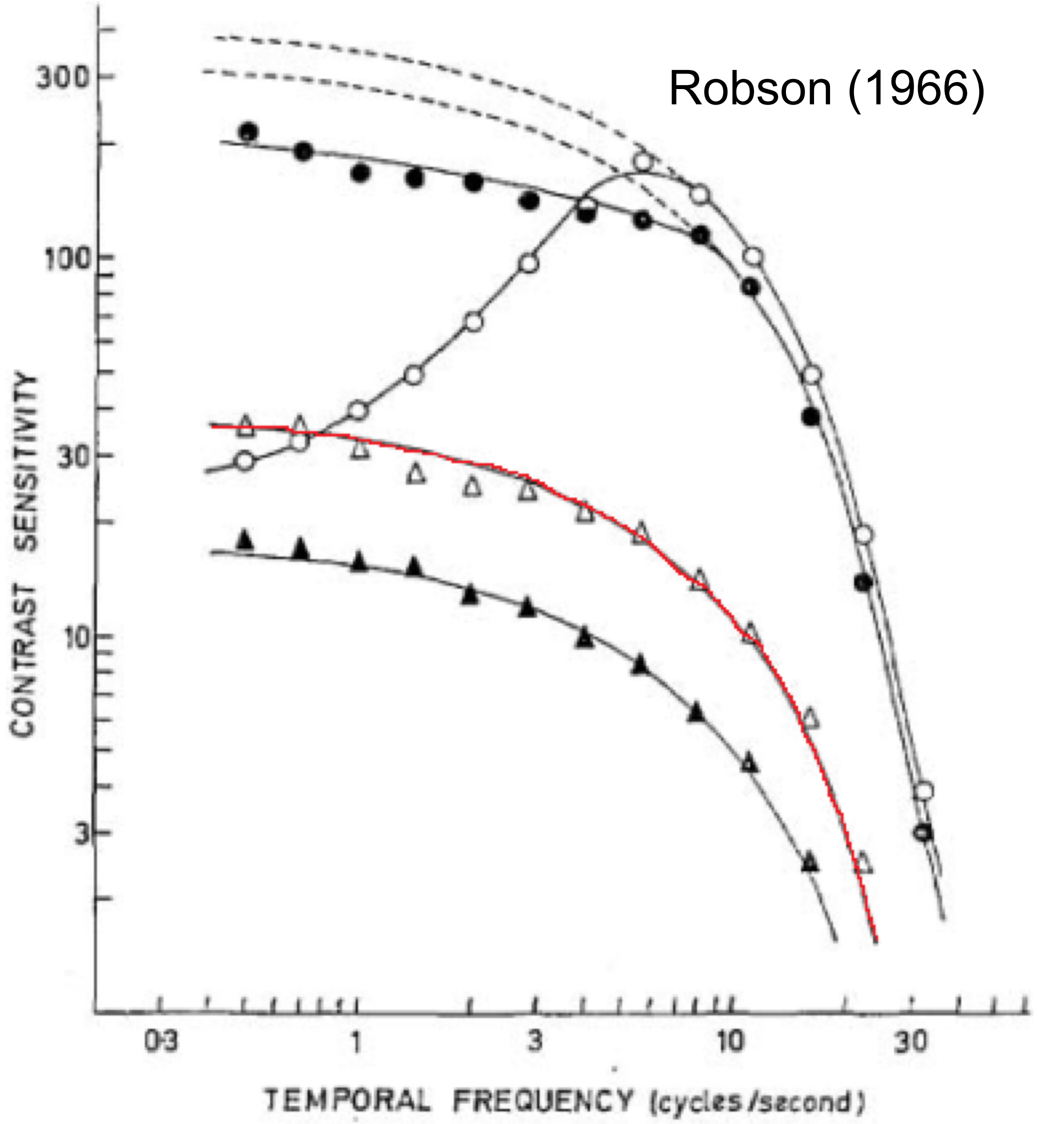
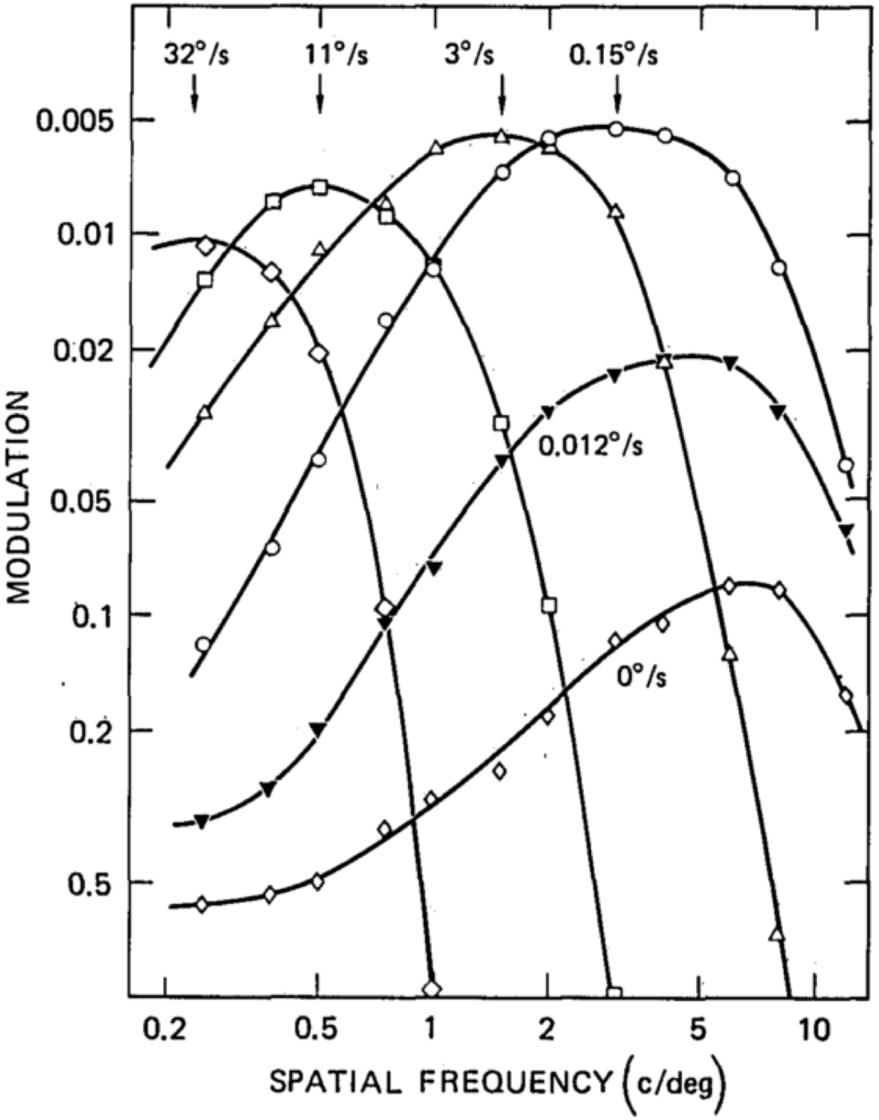
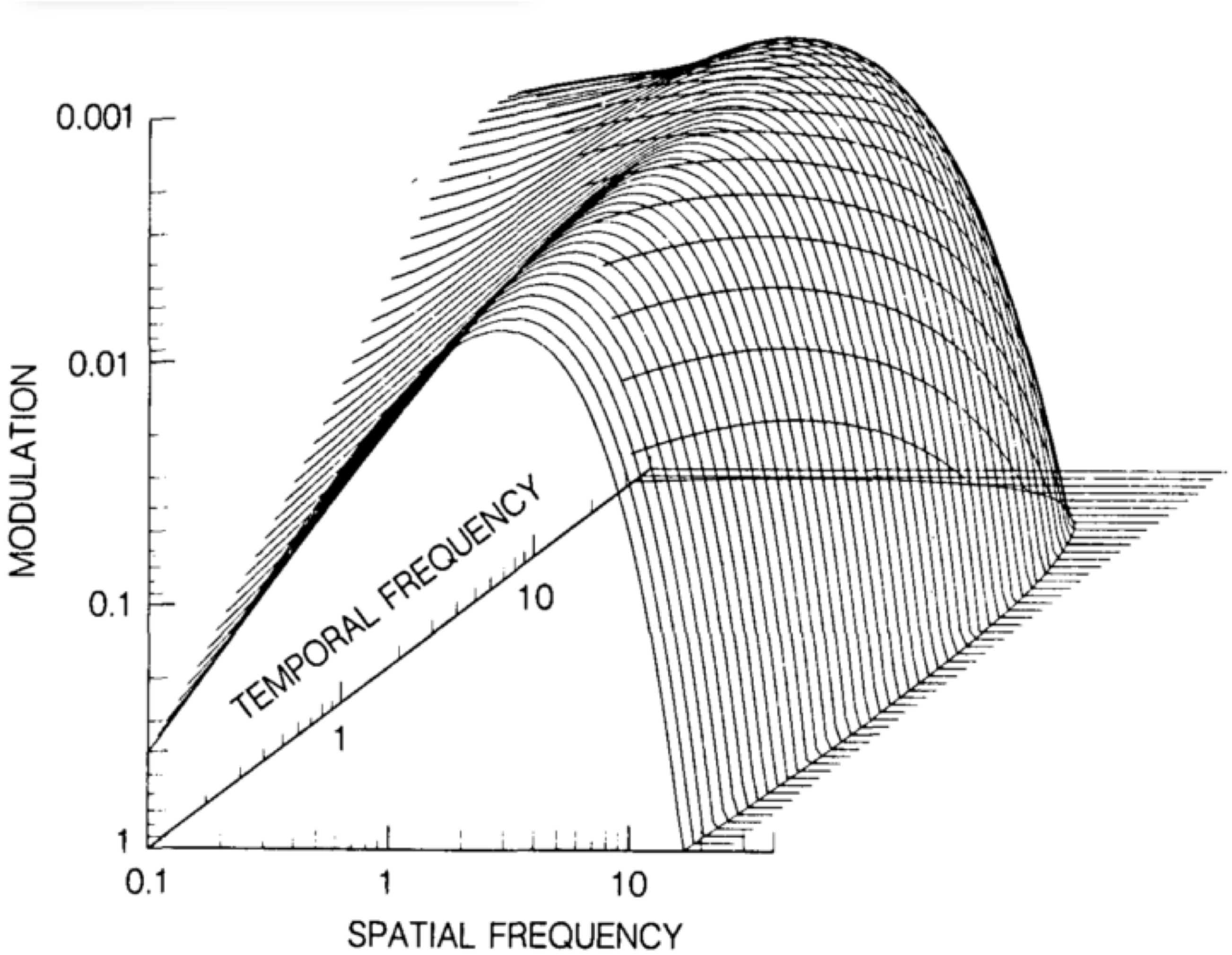


FIG. 2. Temporal contrast-sensitivity (reciprocal of threshold contrast) functions for different spatial frequencies. The points are the means of four measurements and the curves (two with dashed low-frequency sections) differ only in their positions along the contrast-sensitivity scale, ○ 0.5 cycle per degree, ● 4, △ 16, ▲ 22 cycles per degree.

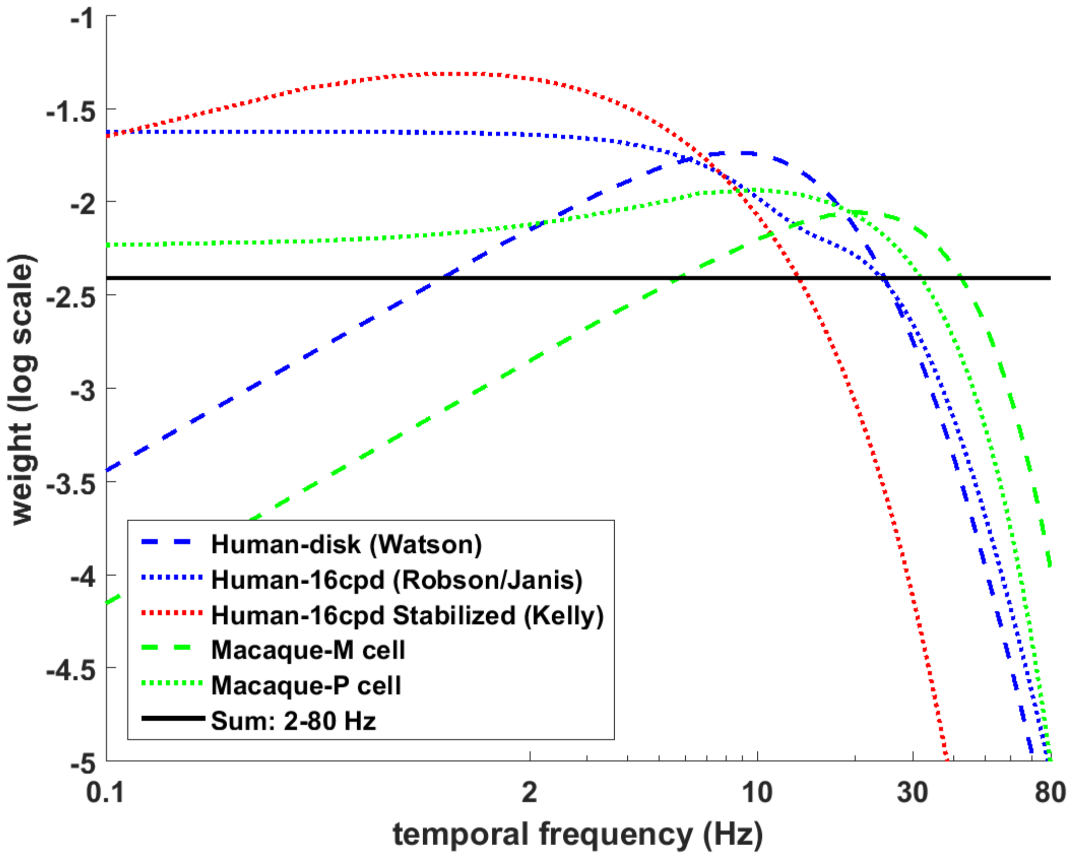
Kelly (1979) - Stabilized

$$G(\alpha,v) = [6.1 + 7.3|\log(v/3)|^3] \times v\alpha^2 \exp[-2\alpha(v + 2)/45.9]. \quad (8)$$





Measured temporal sensitivity functions



- Neurophysiological recordings taken from parafovea (Benardete & Kaplan 1999ab)
- Human temporal sensitivities measured foveally (Watson 1986, Robson 1966, Kelly 1979)

More on spatiotemporal sensitivity

- How does it spatiotemporal sensitivity vary across the retina?
  - P-to-M cell ratio & projections changes with eccentricity (Azzopardi et al 1999)
  - Do the properties of P and M-cells change with eccentricity?
- How does *human* sensitivity vary across the retina?
  - Speed of information processing varies with eccentricity (Carrasco et al 2003)
  - Foveal sensitivity is more lowpass and peripheral sensitivity is more bandpass (Snowden & Hess 1992; Allen & Hess 1992)
  - Sensitivity shape is similar at all retinal locations, just poorer in periphery (Virsu et al 1982, Rovamu et al 1978)
  - Others who have studied temporal sensitivity across the visual field choose eccentricities - fovea, 10deg, 30deg, 60deg (Pointer & Hess 1989)