Ocular Drift: Sensitivity to changes in retinal motion & task-dependence

Janis Intoy

APLab Meeting – June 23, 2020

Overview

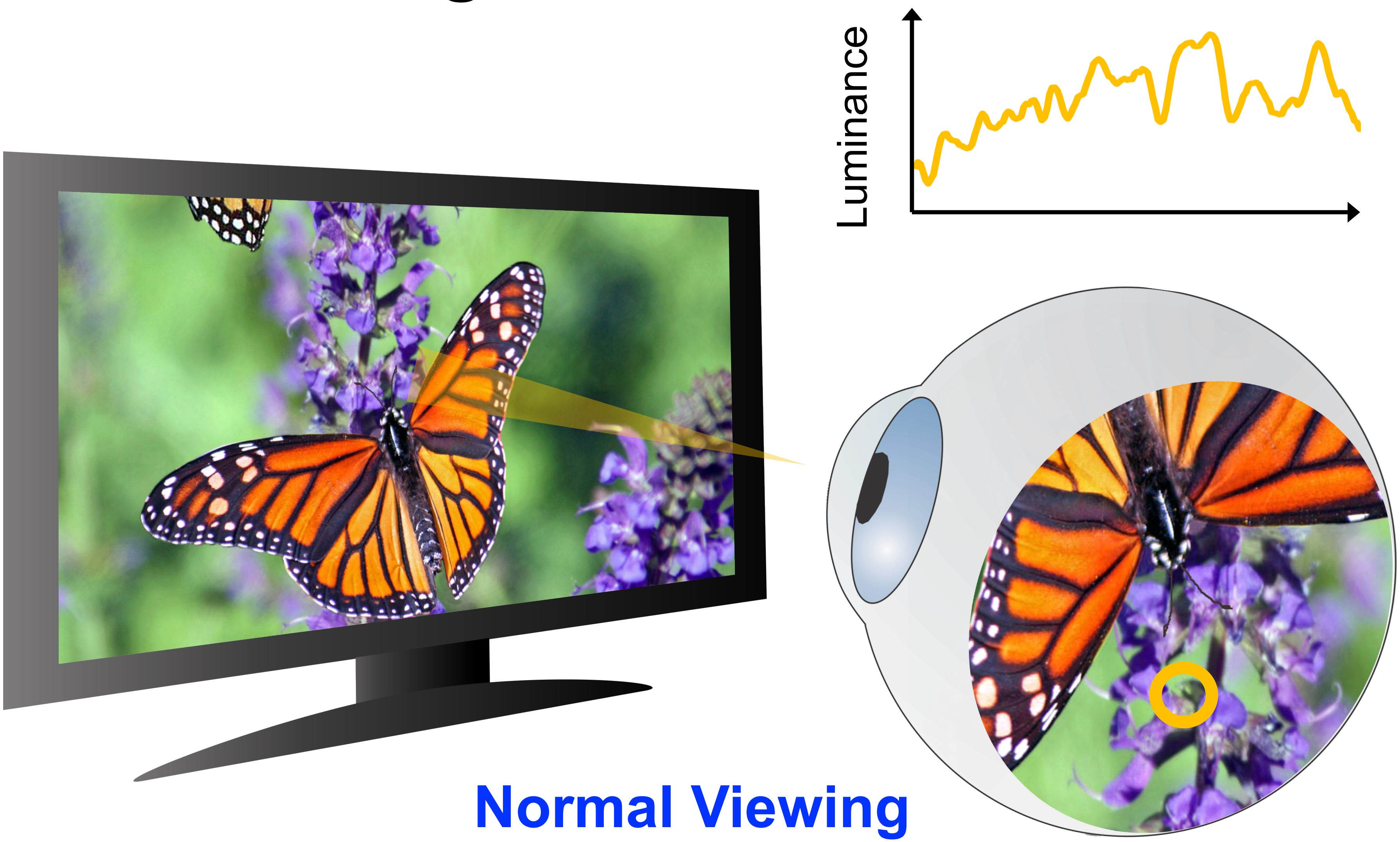
1. Humans are sensitive to changes in retinal image motion from drift
   1. In preparation
   2. how to show effect is not just effect of manipulation?

2. Task-dependent control of drift
   1. Characteristics of drifts
   2. Brownian
   3. Long-term temporal correlations

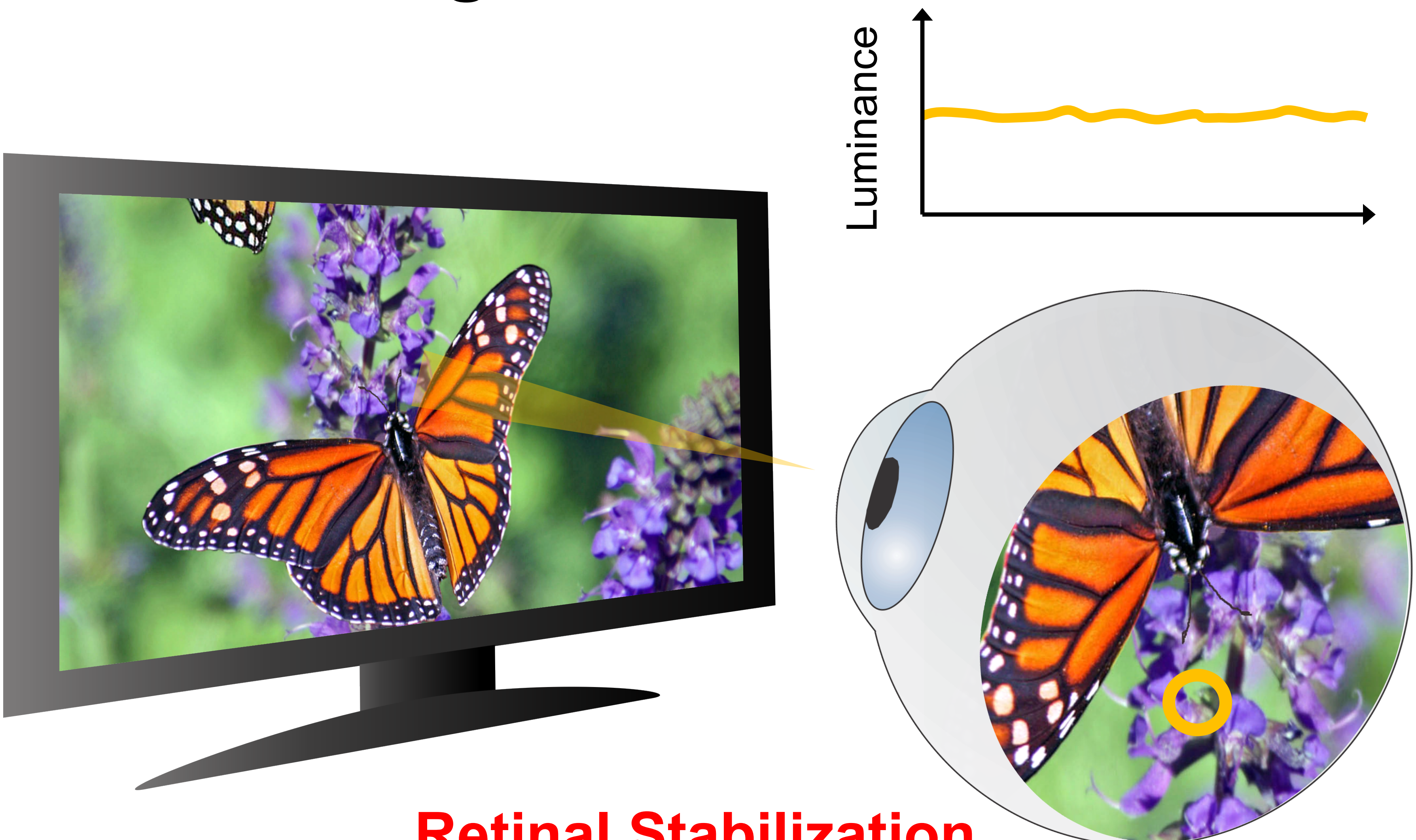
1. Humans utilize temporal transients from ocular drift for fine spatial discriminations (Rucci et al, 2007; Boi et al, 2017)
2. In a high acuity task, the characteristics of ocular drift change to provide greater temporal power at high spatial frequencies (Intoy & Rucci, 2020).

Does visibility depend on the temporal power of luminance modulations delivered by eye movements?

Controlling retinal stimulation

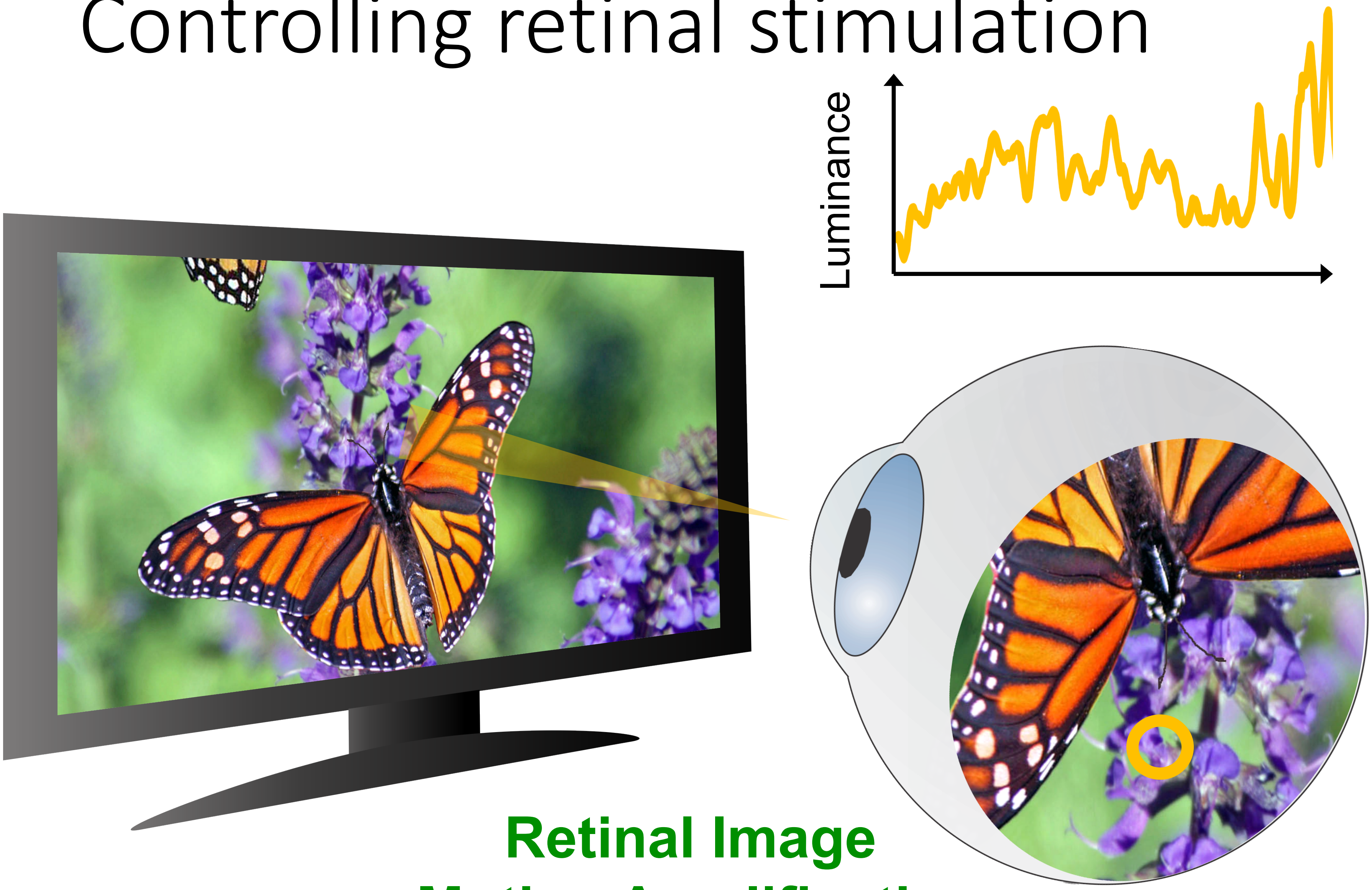


Controlling retinal stimulation



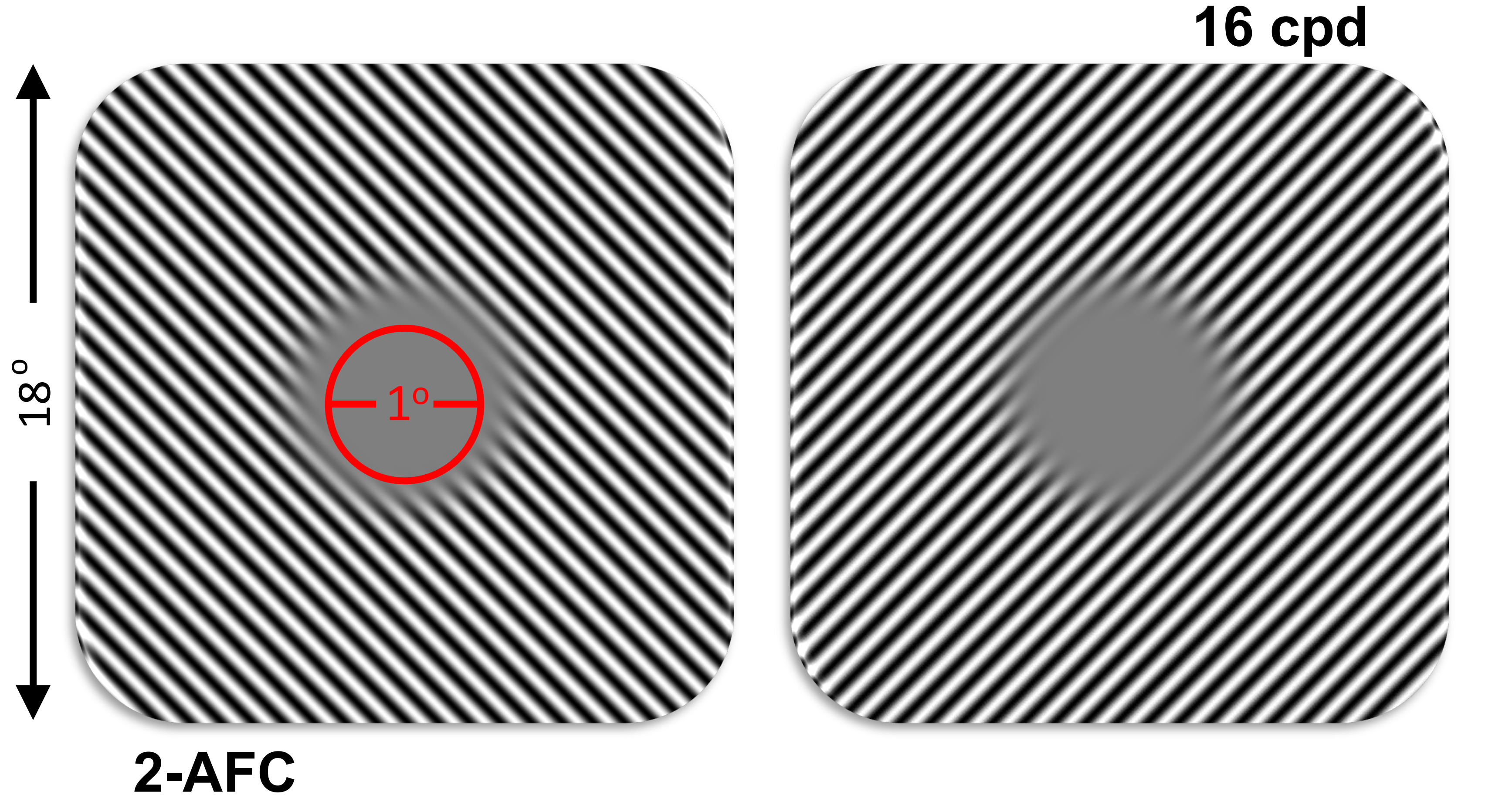
Retinal Stabilization

Controlling retinal stimulation

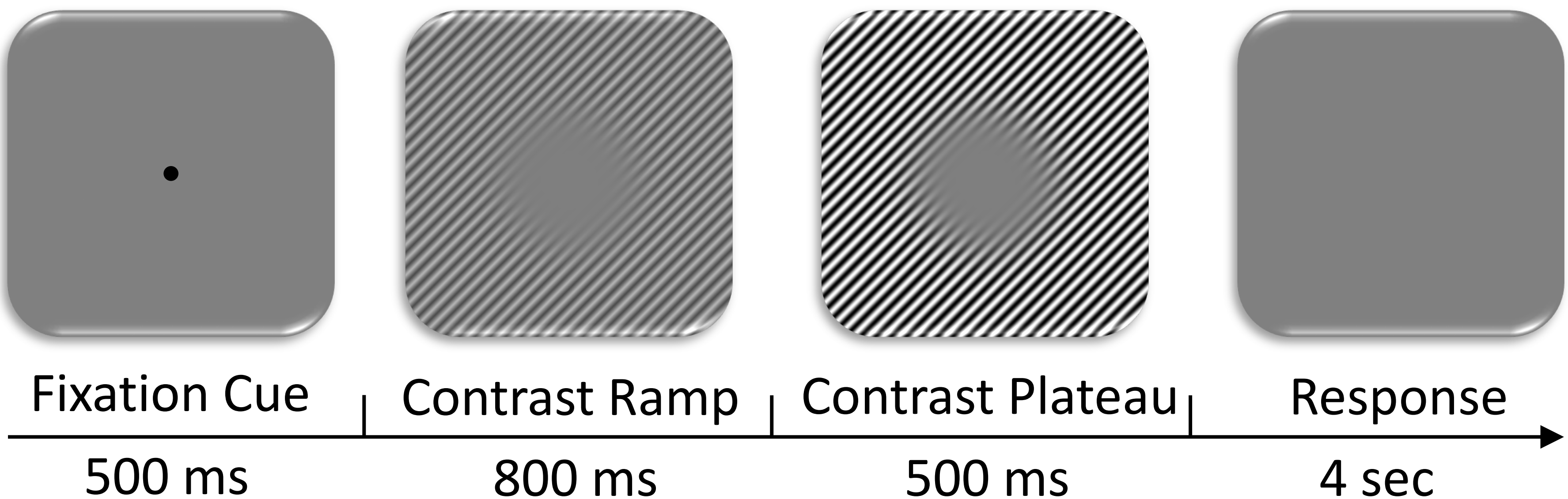


Retinal Image
Motion Amplification

Stimulus



Trial flow

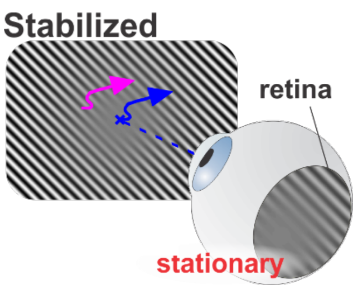


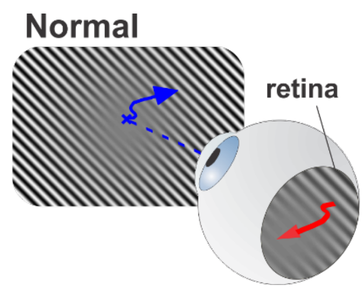
Normal or Manipulated grating

L or R?

Manipulating retinal image motion

- eye motion
- stimulus motion
- retinal image motion

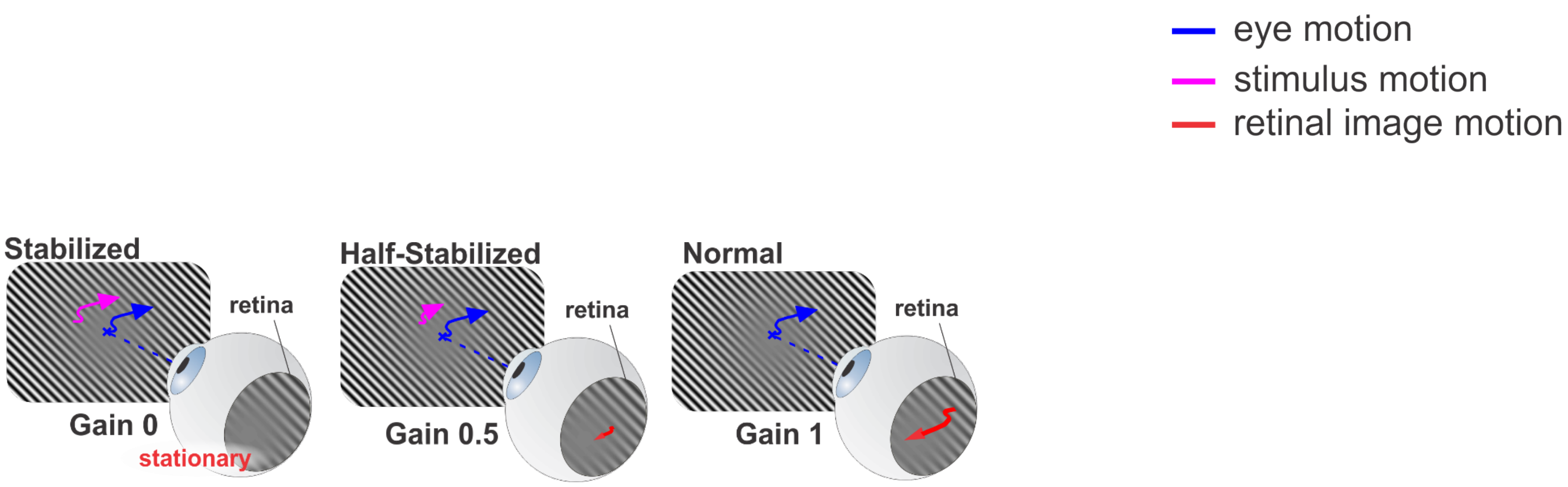




Less Retinal Image Motion from Drift

More Retinal Image Motion from Drift

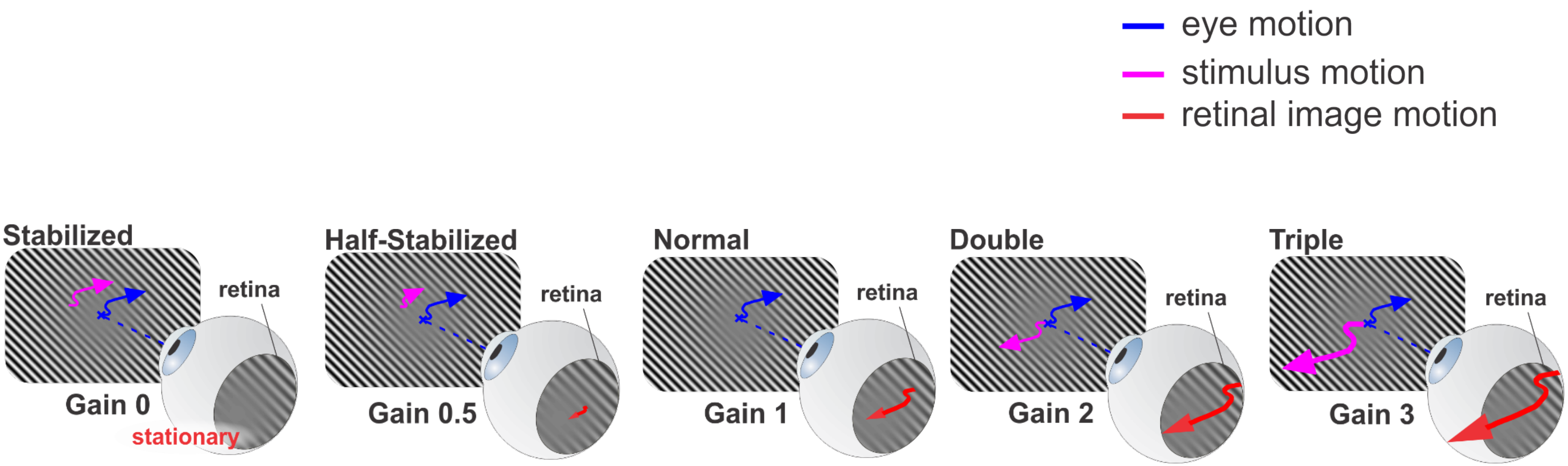
Manipulating retinal image motion



Less Retinal Image Motion from Drift

More Retinal Image Motion from Drift

Manipulating retinal image motion

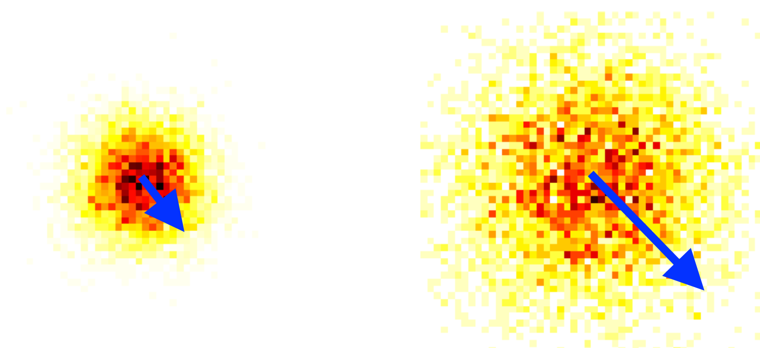


Less Retinal Image Motion from Drift

More Retinal Image Motion from Drift

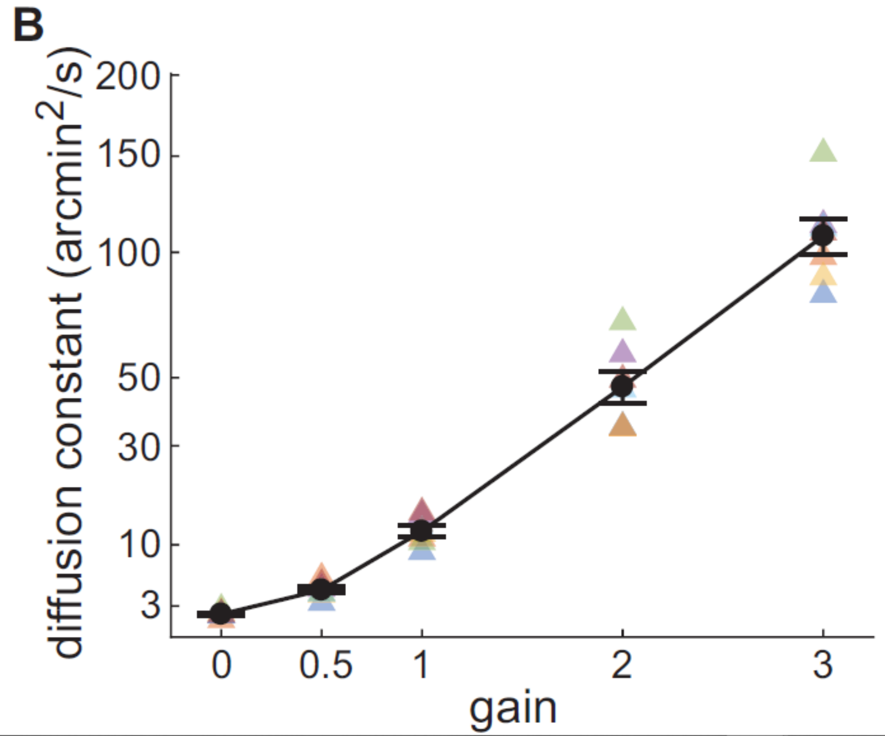
Quantifying retinal image motion

Probability of gaze displacement over time

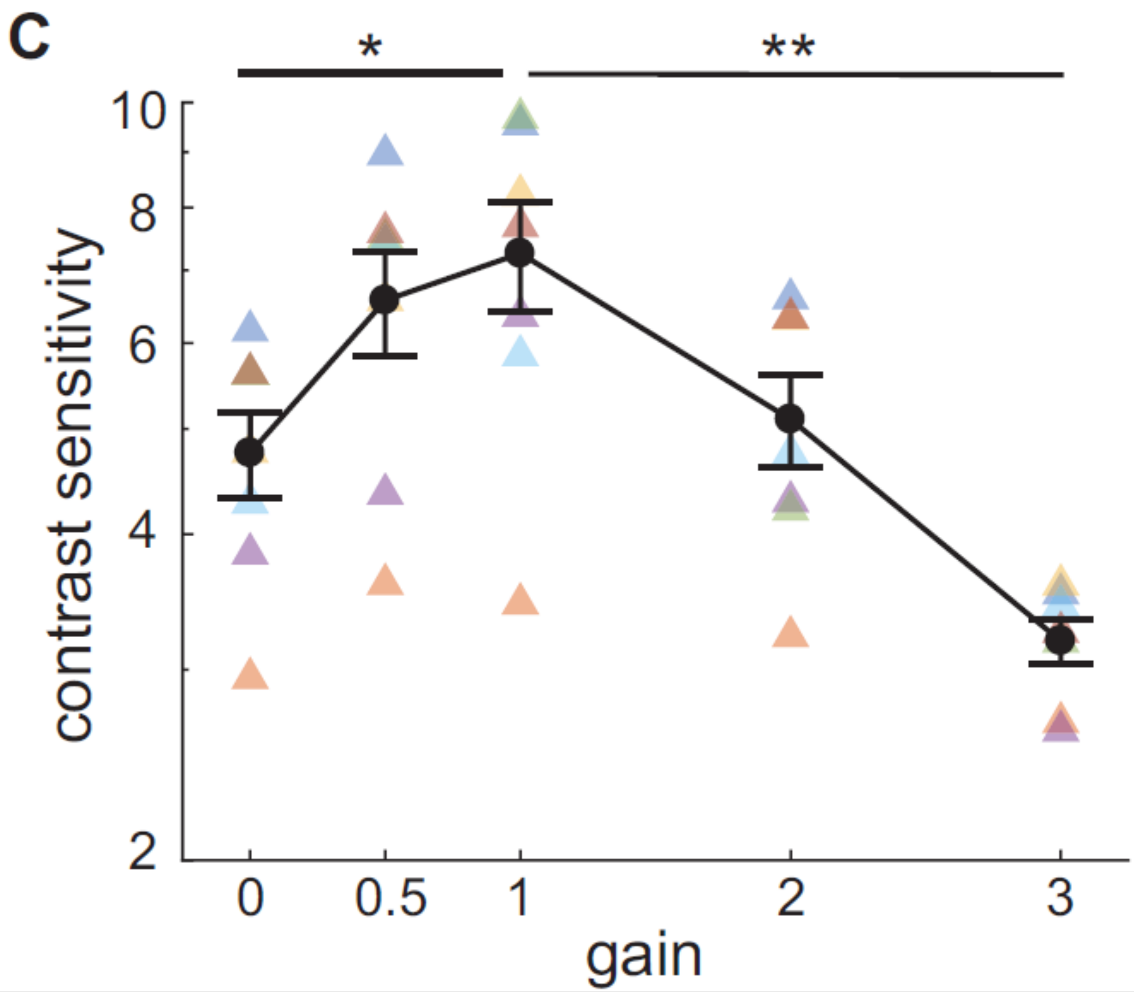


smaller larger

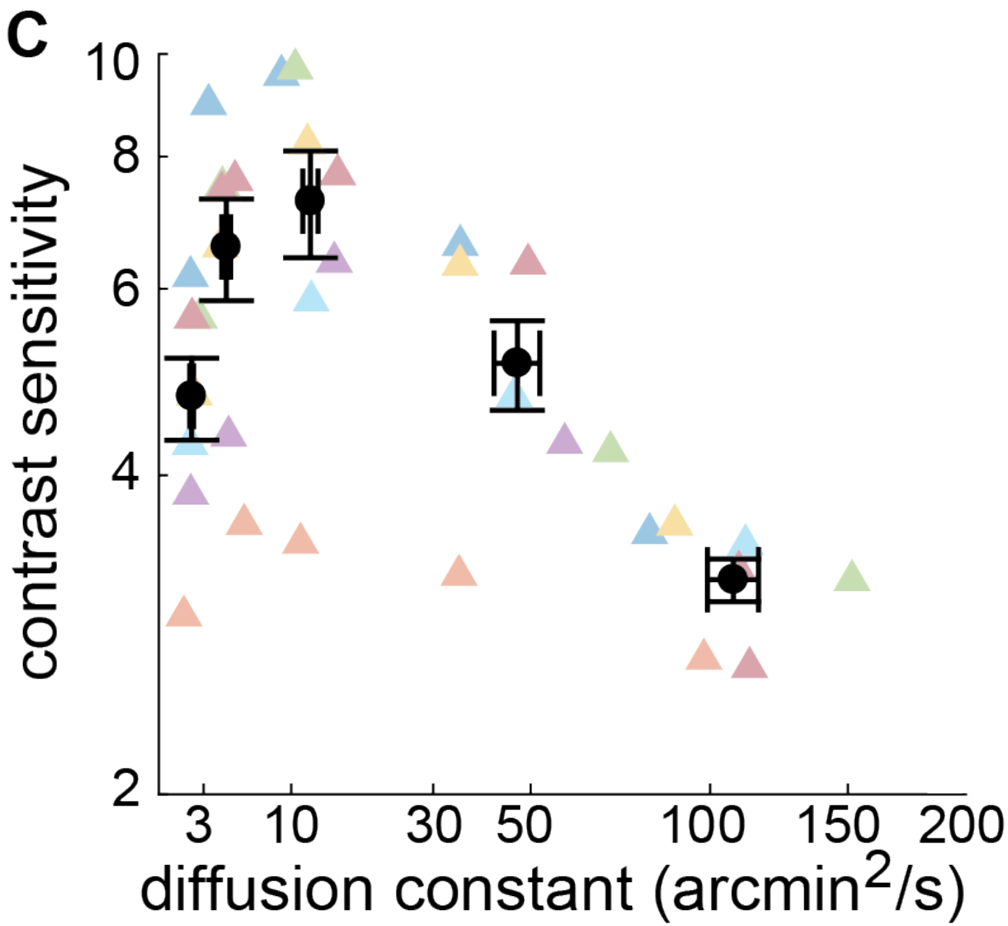
Diffusion Constant



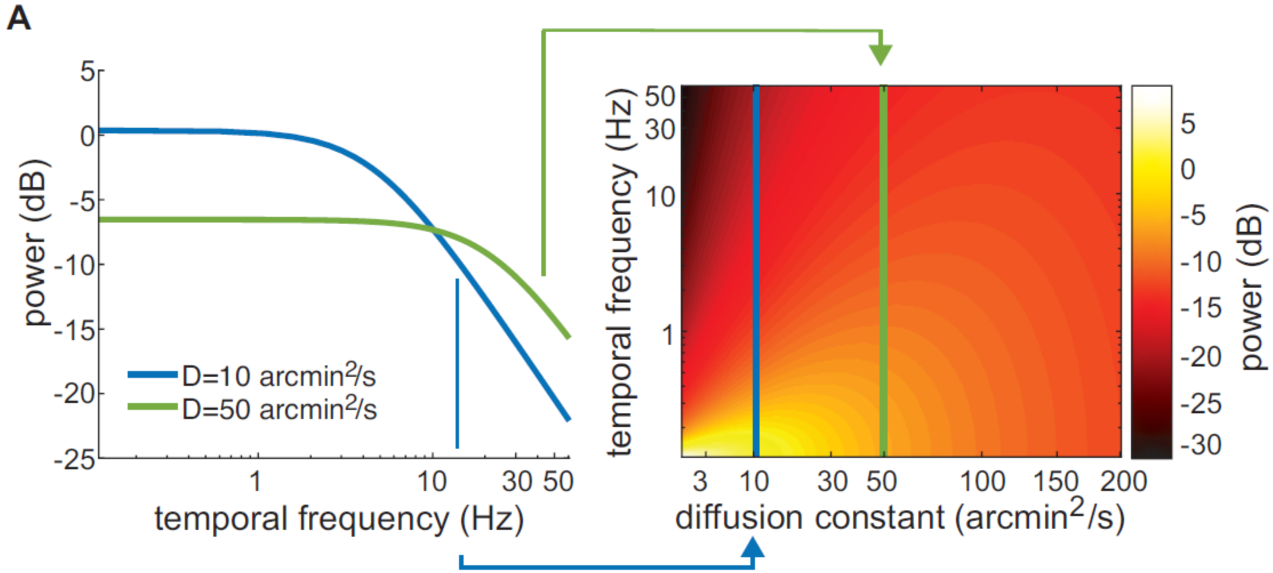
Contrast Sensitivity



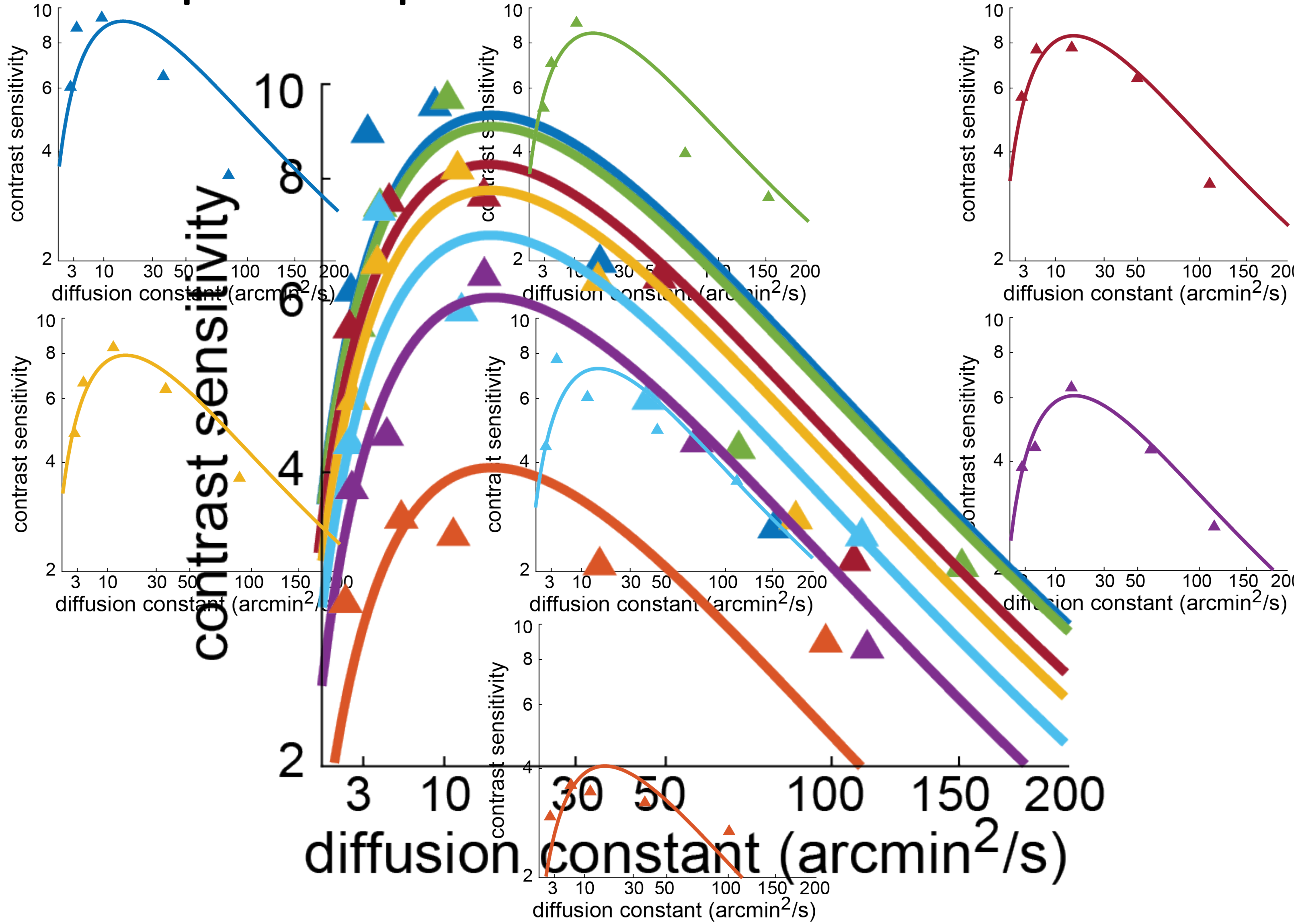
Temporal power from drift



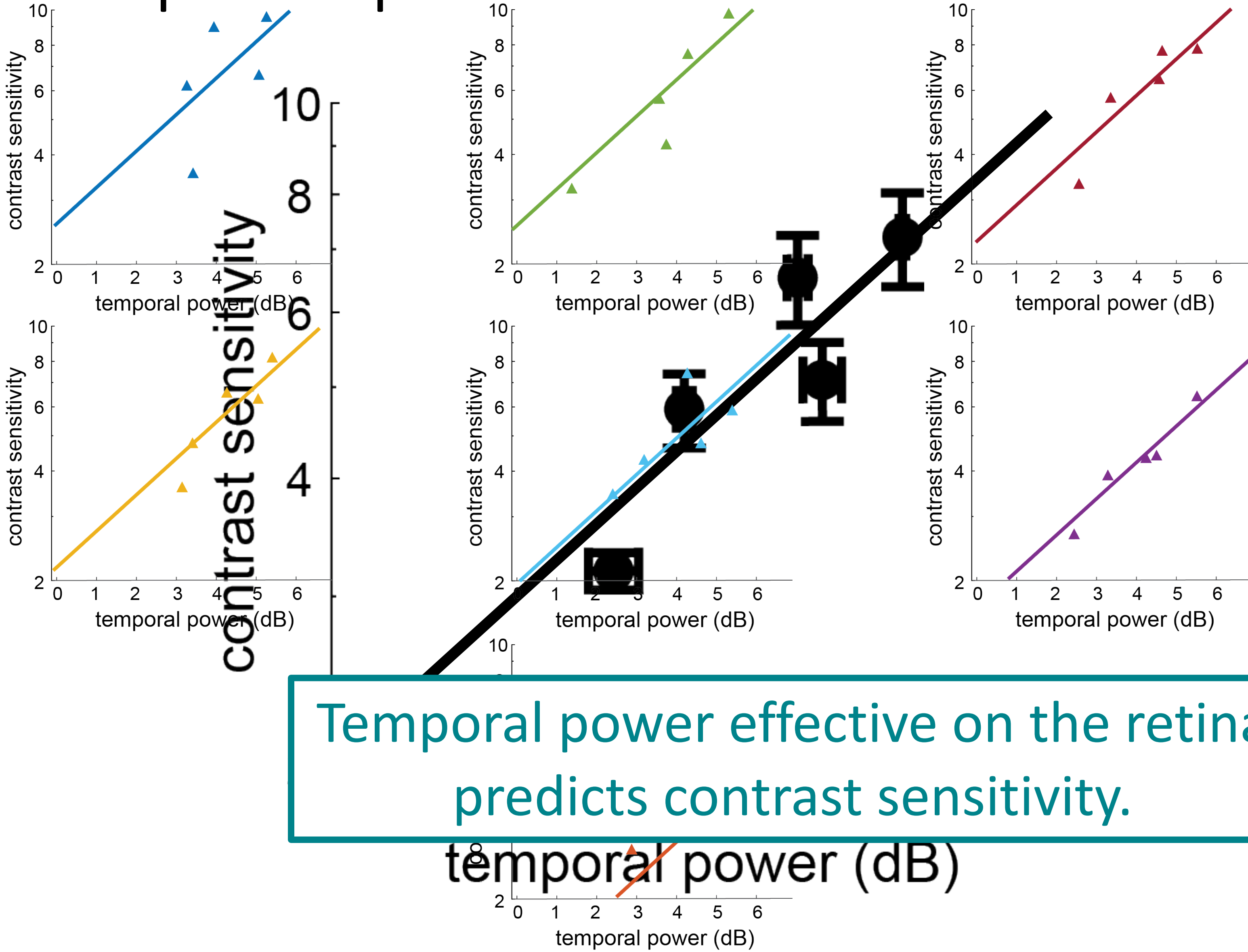
Temporal power from drift



Temporal power from drift



Temporal power from drift



Temporal power effective on the retina predicts contrast sensitivity.

Does contrast sensitivity depend on temporal power?

Or

Does manipulation of retinal image motion impair sensitivity?

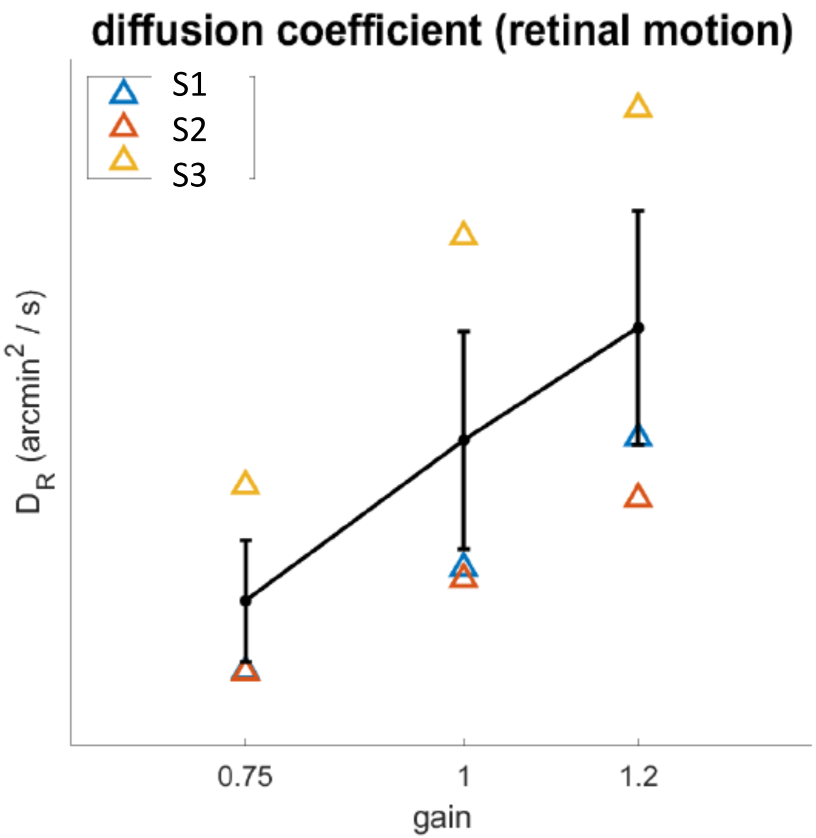
1. Comparison of *normal* trials with more/less retinal image motion
2. Condition in which retinal image motion is manipulated but provides same temporal power as normal condition
   - Collect new data: (examples: gain = -1 or playback of other trials)
3. Condition in which visual sensitivity benefits from more (or less) retinal image motion compared to normal
   - Examine previous data set with 10cpd gratings

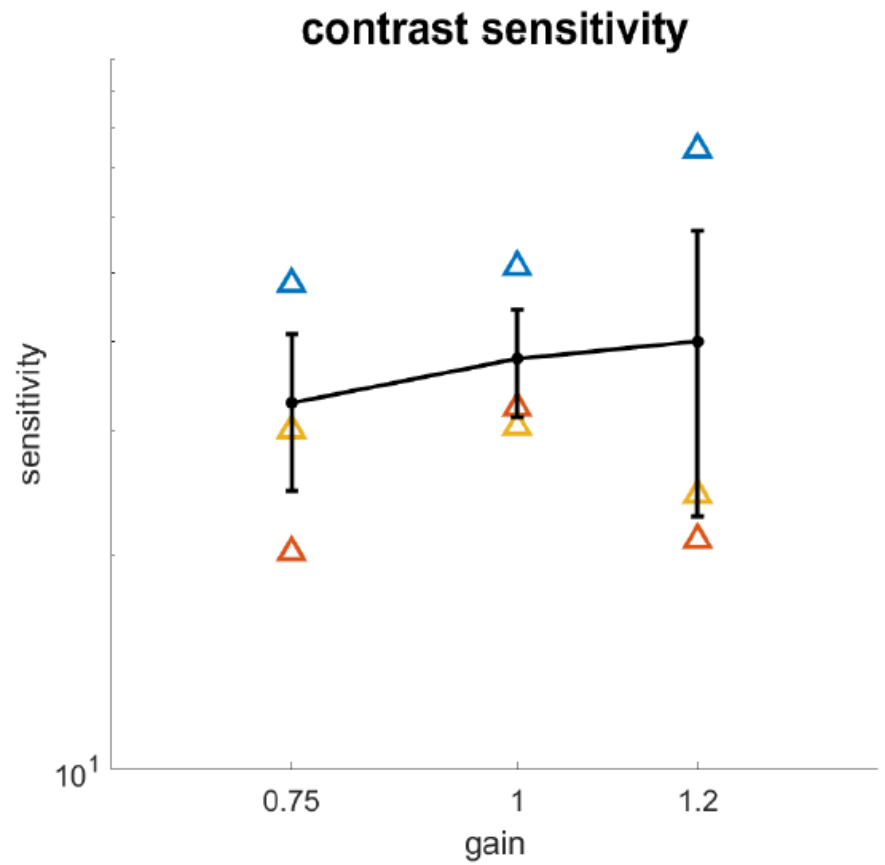
10 cpd

- Same task now with
  - 10cpd gratings
  - Gain conditions [0.75, 1, 1.2]

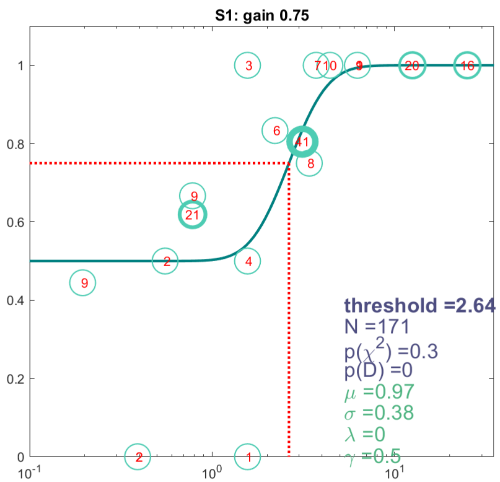
Subject	Total	Drift Only Trials			Invalid		
		Gain = 0.75	Gain = 1.00	Gain = 1.20	ND/NT/B	S	MS
S1	1013	187 155	237 174	193 139	91	142	163
S2	1526	253 107	279 101	257 104	468	100	169
S3	1625	329 128	276 94	369 115	349	108	194

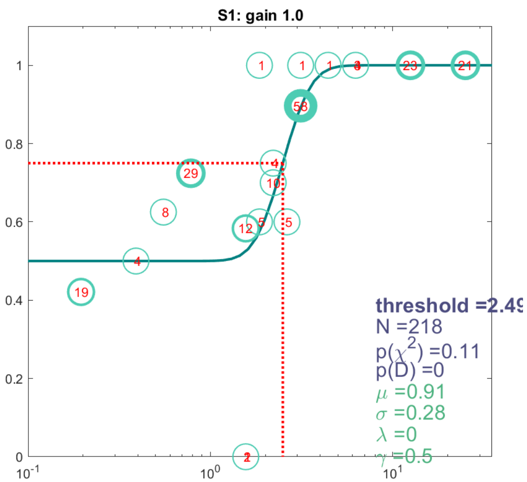
Data Summary

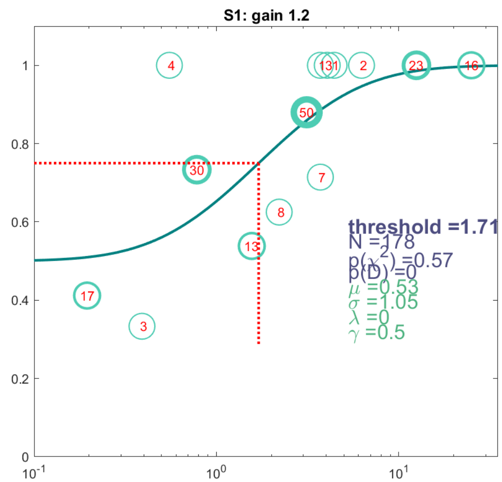


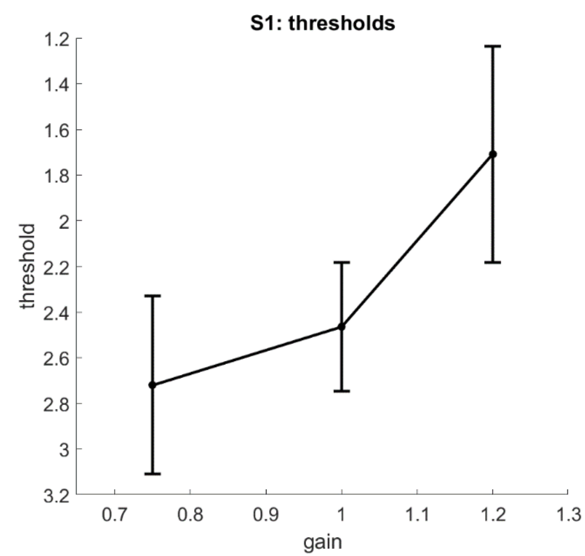


S1

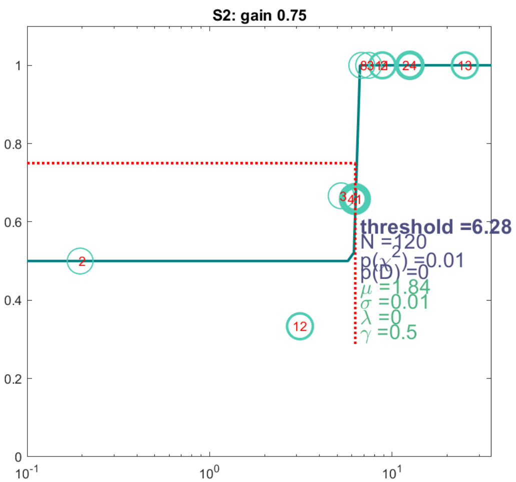

S1: gain 0.75
threshold =2.64
N =171
p(χ^2) =0.3
p(D) =0
μ =0.97
σ =0.38
λ =0
γ =0.5

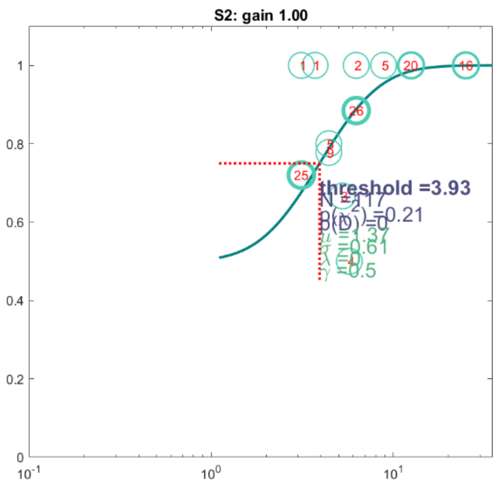

S1: gain 1.0
N =218
p(χ^2) =0.11
p(D) =0
μ =0.91
σ =0.28
λ =0
γ =0.5

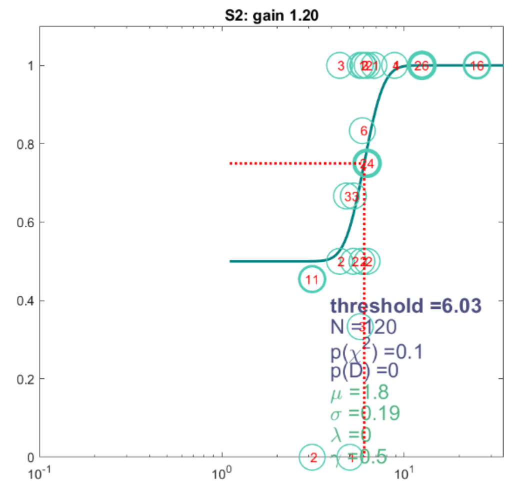

S1: gain 1.2
threshold =1.71
N =178
p(χ^2) =0.57
p(D) =0
μ =0.53
σ =1.05
λ =0
γ =0.5

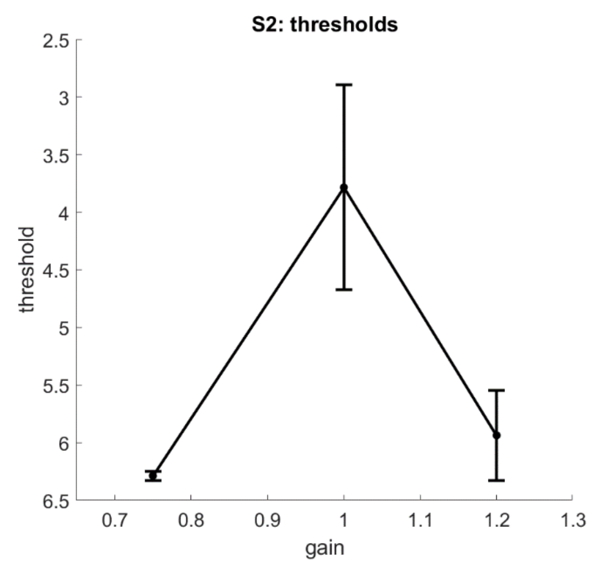

S1: thresholds
threshold
gain

S2

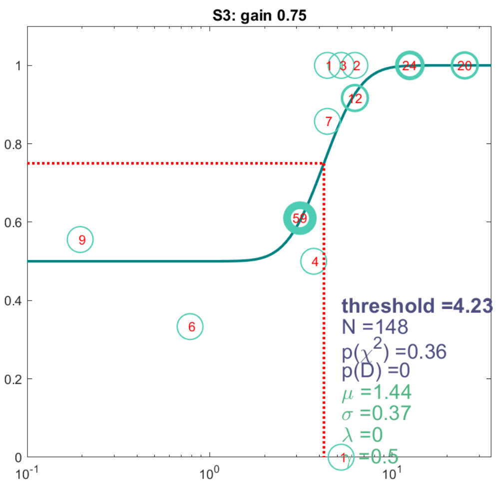

S2: gain 0.75
threshold =6.28
N =120
p(χ2) =0.01
p(D) =0
μ =1.84
σ =0.01
λ =0
γ =0.5

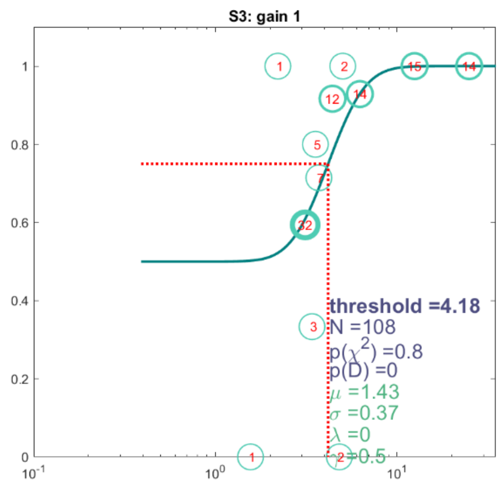

S2: gain 1.00
threshold =3.93
N =117
p(χ2) =0.21
p(D) =0
μ =1.37
σ =0.61
λ =0
γ =0.5

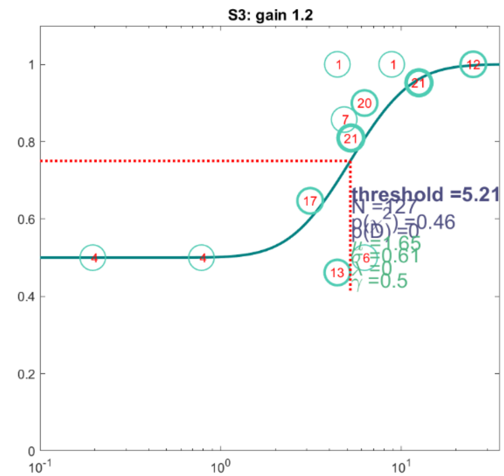

S2: gain 1.20
threshold =6.03
N =120
p(χ2) =0.1
p(D) =0
μ =1.8
σ =0.19
λ =0
γ =0.5

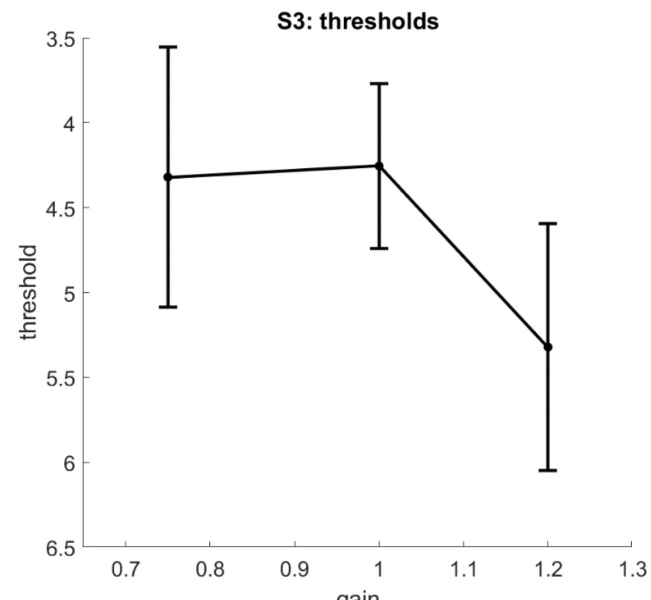

S2: thresholds
threshold
gain

S3

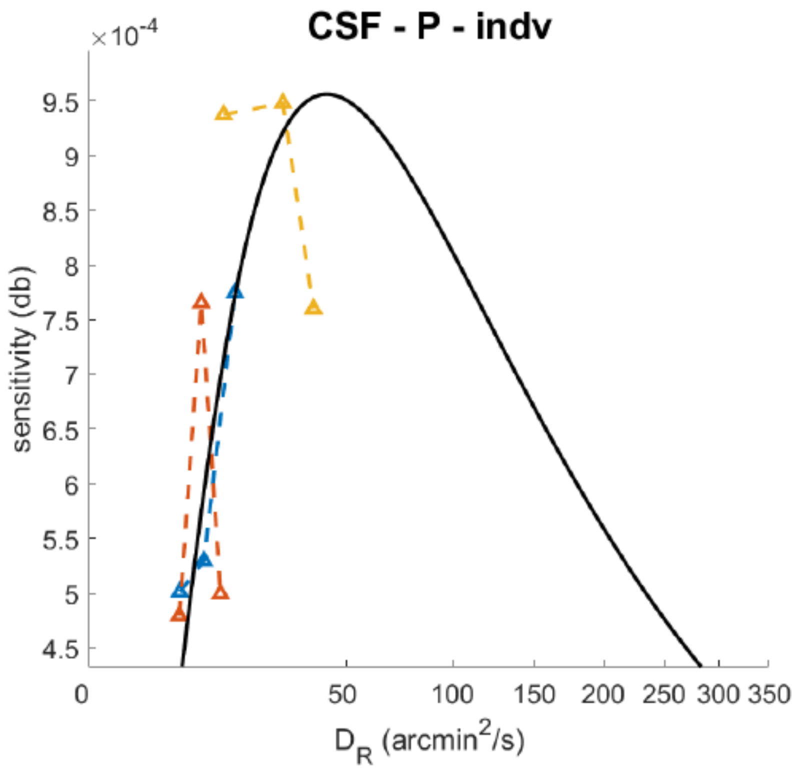

S3: gain 0.75
threshold =4.23
N =148
p(χ^2) =0.36
p(D) =0
μ =1.44
σ =0.37
λ =0

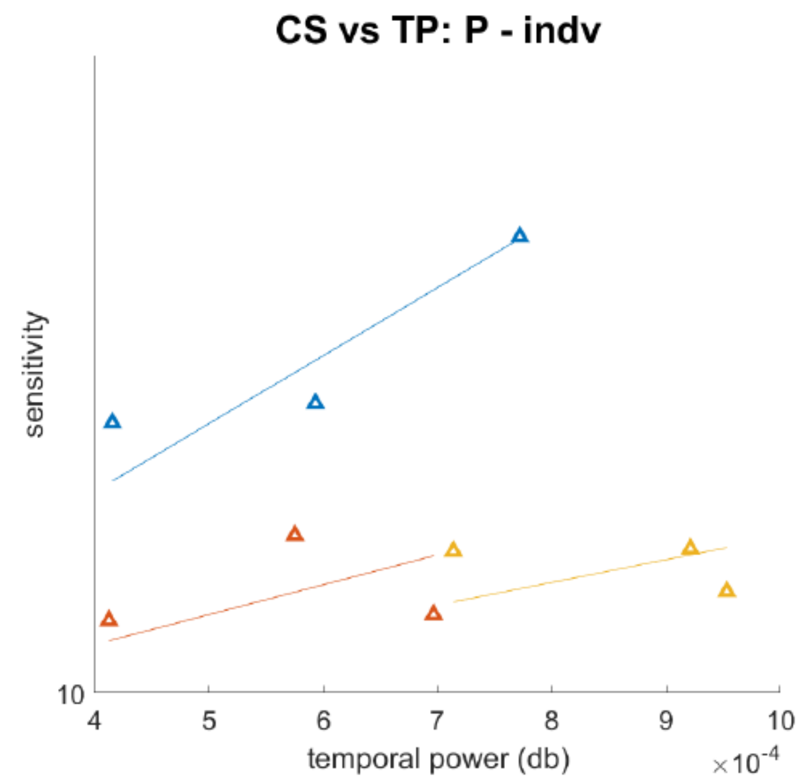

S3: gain 1
threshold =4.18
N =108
p(χ^2) =0.8
p(D) =0
μ =1.43
σ =0.37
λ =0


S3: gain 1.2
threshold =5.21
γ =0.5


S3: thresholds
threshold
gain

10cpd


CSF - P - indv
×10^-4
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
sensitivity (db)
0
50
100
150
200
250
300
350
D_R (arcmin^2/s)


CS vs TP: P - indv
sensitivity
10
4
5
6
7
8
9
10
temporal power (db)
×10^-4

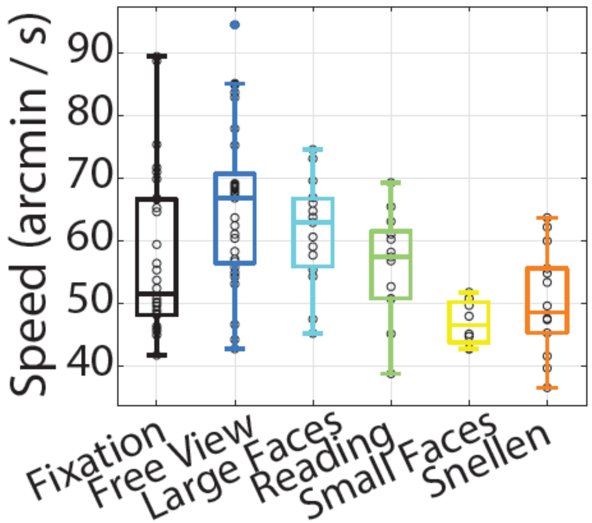
Overview

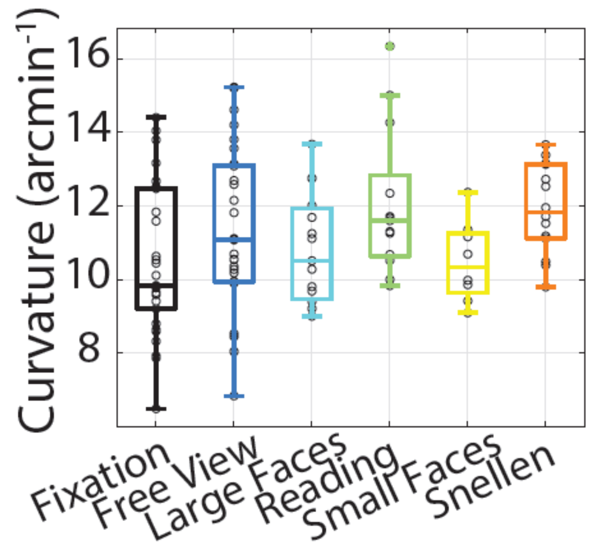
1. Humans are sensitive to changes in retinal image motion from drift
   1. In preparation
   2. how to show effect is not just effect of manipulation?

2. Task-dependent control of drift
   1. Characteristics of drifts
   2. Brownian
   3. Long-term temporal correlations

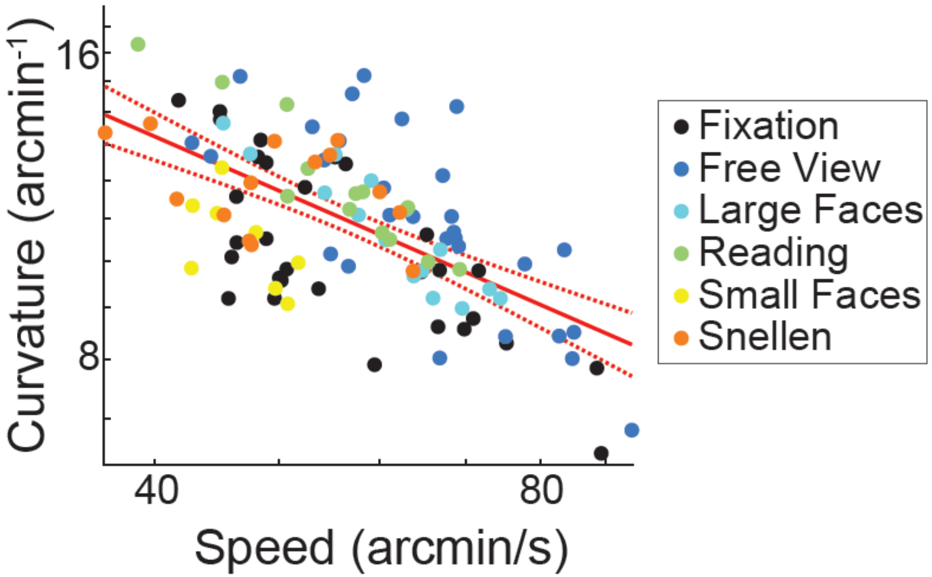
Task-dependent control of drift

Mean speed and curvature varies considerably across individuals, regardless of task. **Drift speed varied significantly depending on the task** (ANOVA $F(5, 103)=6.18$, $p<10^{-4}$). In contrast, curvature remained constant.





Task-dependent control of drift



Drift speed and curvature are inversely correlated ($r=-0.62$, $p<10^{-4}$).

Faster drifts tend to curve less than slower drifts.

Brownian Motion model of ocular drift

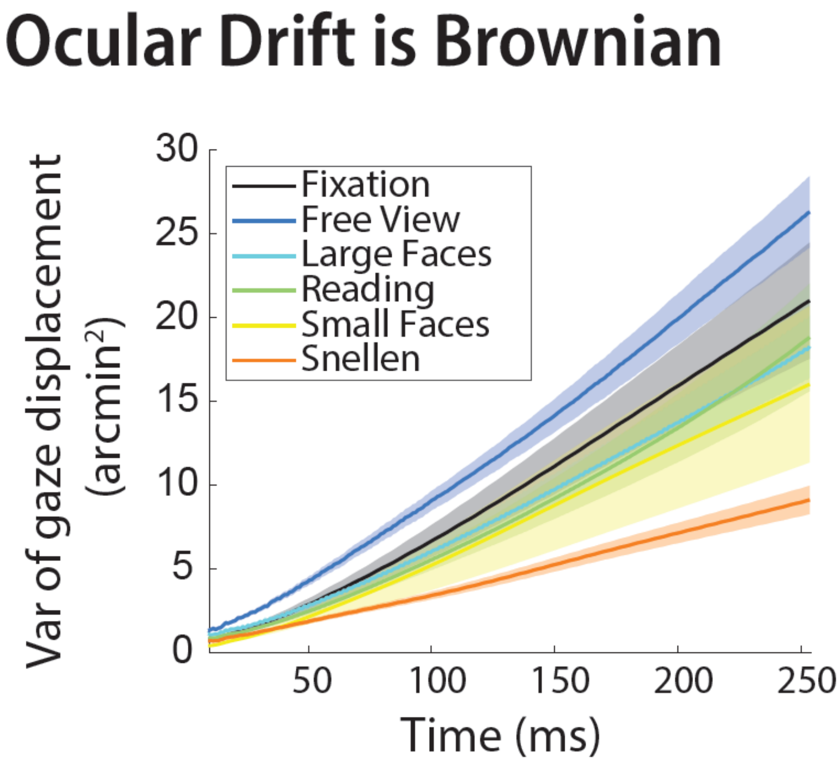
- Brownian motion model of drift has helped us understand the visual functions of drift and explain empirical results

Brownian Motion model of ocular drift

- Brownian Motion model of drift has helped us understand the visual functions of drift and explain empirical results

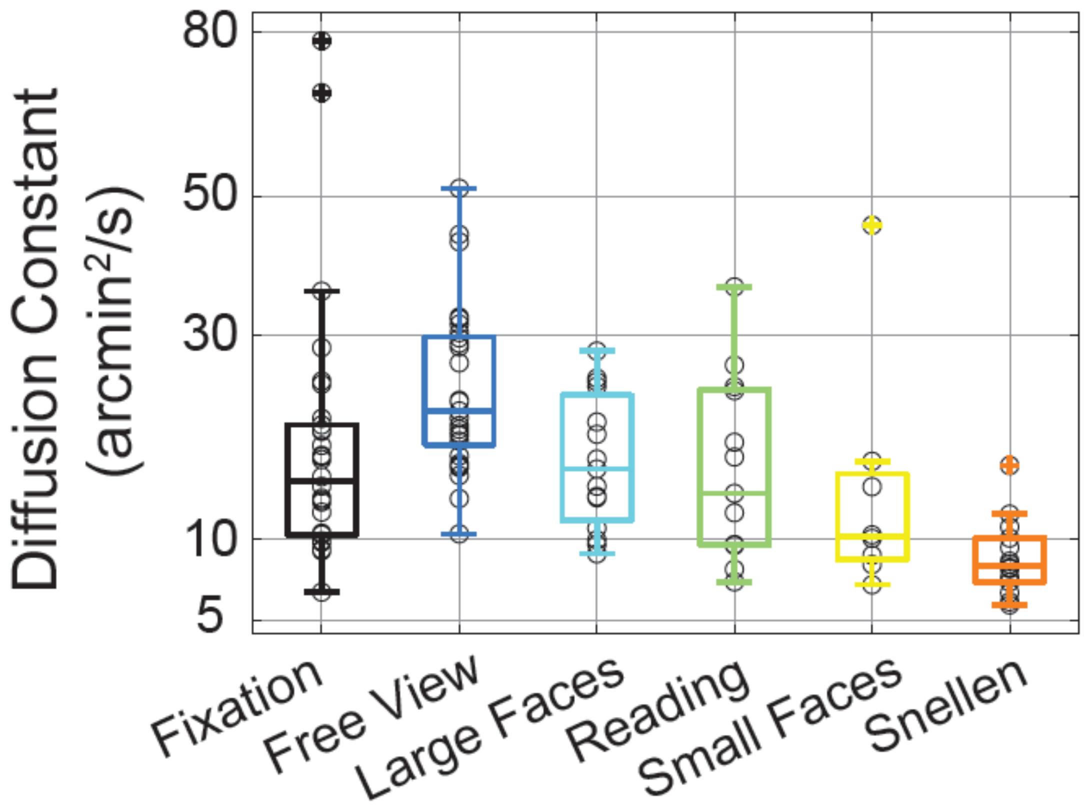
1. Spatial whitening (removing redundancy from visual input) (Kuang et al, 2012)
2. Selective enhancement of high spatial frequency in images (Rucci et al, 2007; Boi et al, 2017)
3. Predictions:
    1. “optimal” drift diffusion by spatial frequency
    2. Sensitivity depends on temporal power from drift (Intoy et al, in prep)

Is Brownian motion a good model of drift?



In all tasks, the overall characteristics of ocular drift are compatible with a Brownian motion model. The variance of gaze displacement increases linearly with time, a signature of Brownian motion ($R^2 > 0.95$). However, the diffusion constant, the slope of the increase, varies with task.

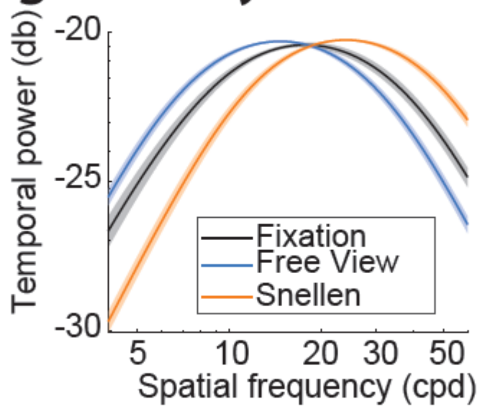
Task-dependent control of drift



The diffusion constant (which captures changes in speed and curvature) is one parameter by which drift may be controlled.

Task-dependent control of drift

High-acuity drifts enhance fine details

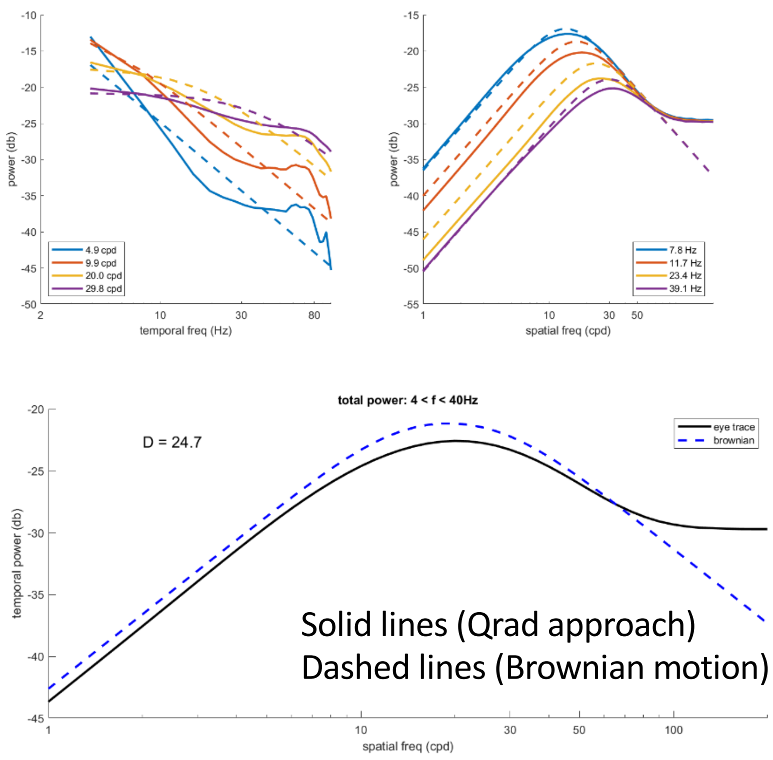


Drift transforms space into a spatiotemporal flow on the retina. Here we examine how spatial information is redistributed by drifts from several tasks.

Luminance modulations from drifts during the Snellen task posses greater power at high spatial frequencies compared to fixation and free viewing.

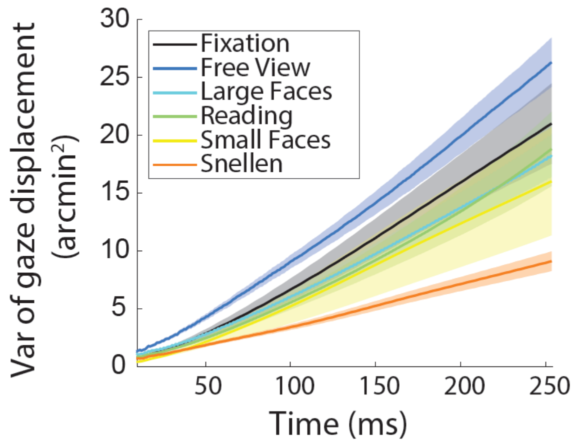
Is Brownian motion a good model of drift?

BM model well captures the spatiotemporal characteristics of retinal input during drifts.



Is Brownian motion a good model of drift?

- Investigate long-term correlations present in drifts.
- BM is uncorrelated in time.
- Fractional Brownian motion (fBM) has a parameter for temporal correlations (Hurst index, H)



Brownian Motion(BM):

$<r^2> = 4Dt$

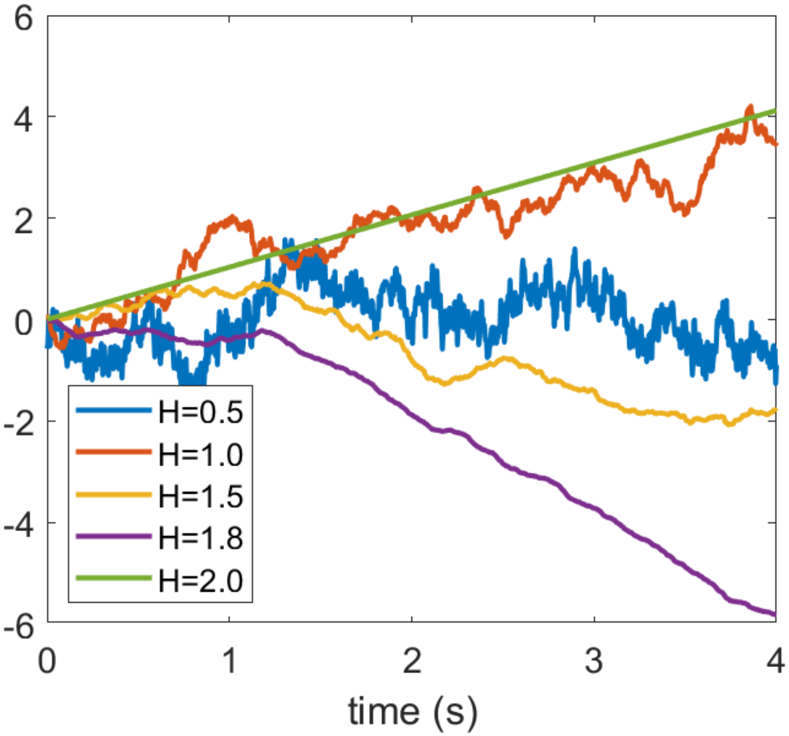
Fractional Brownian Motion (fBM):

$<r^2> = 4Dt^H$

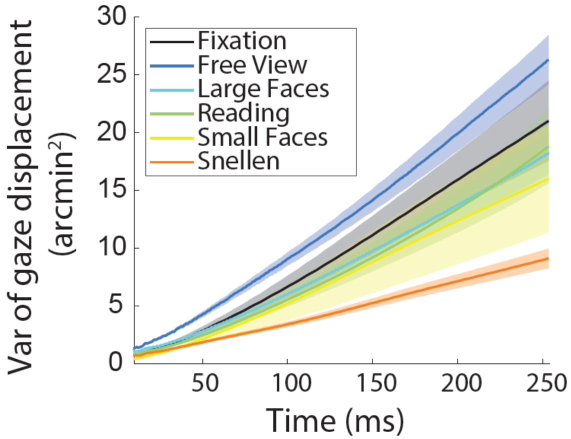
$H = 1 \rightarrow$ Brownian Motion

Fractional Brownian Motion: examples

Relationship to long-term correlations:
H > 1 : correlated in time
H = 1: uncorrelated in time (BM)
H < 1: anticorrelated in time



Temporal correlations



Brownian Motion(BM):

$\langle r^2 \rangle = 4Dt$

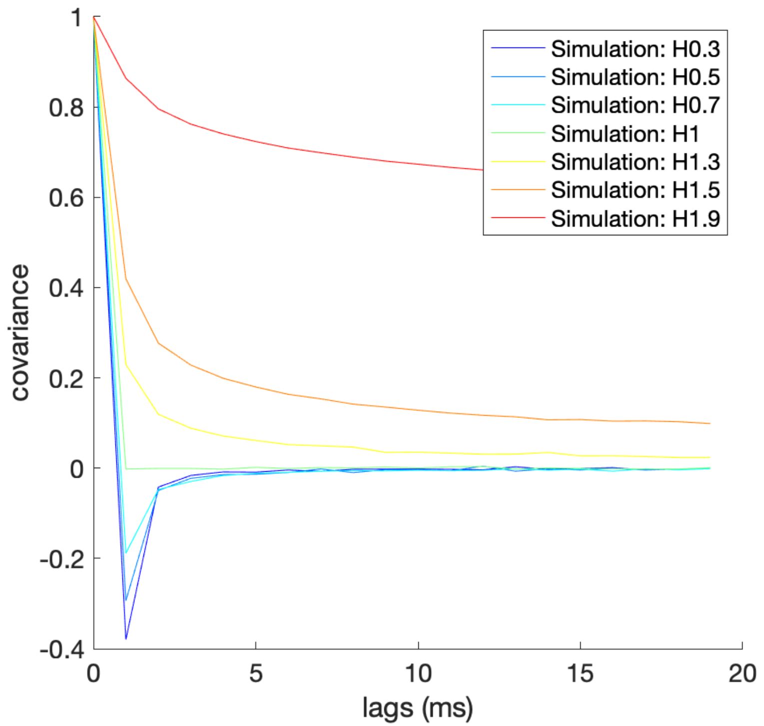
Fractional Brownian Motion (fBM):

$\langle r^2 \rangle = 4Dt^H$

$H = 1 \rightarrow$ Brownian Motion

1. Examine covariance of step size across time
2. Estimate H (by regression or DFA)

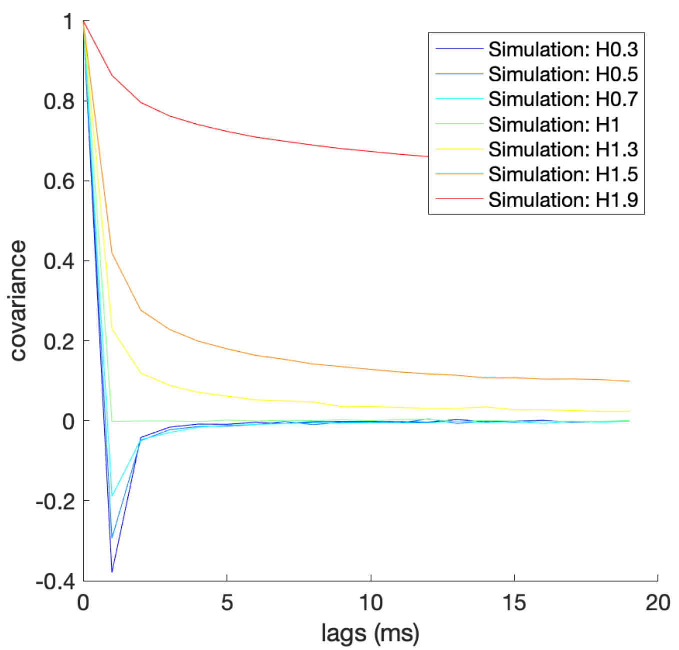
Temporal correlations in fBM

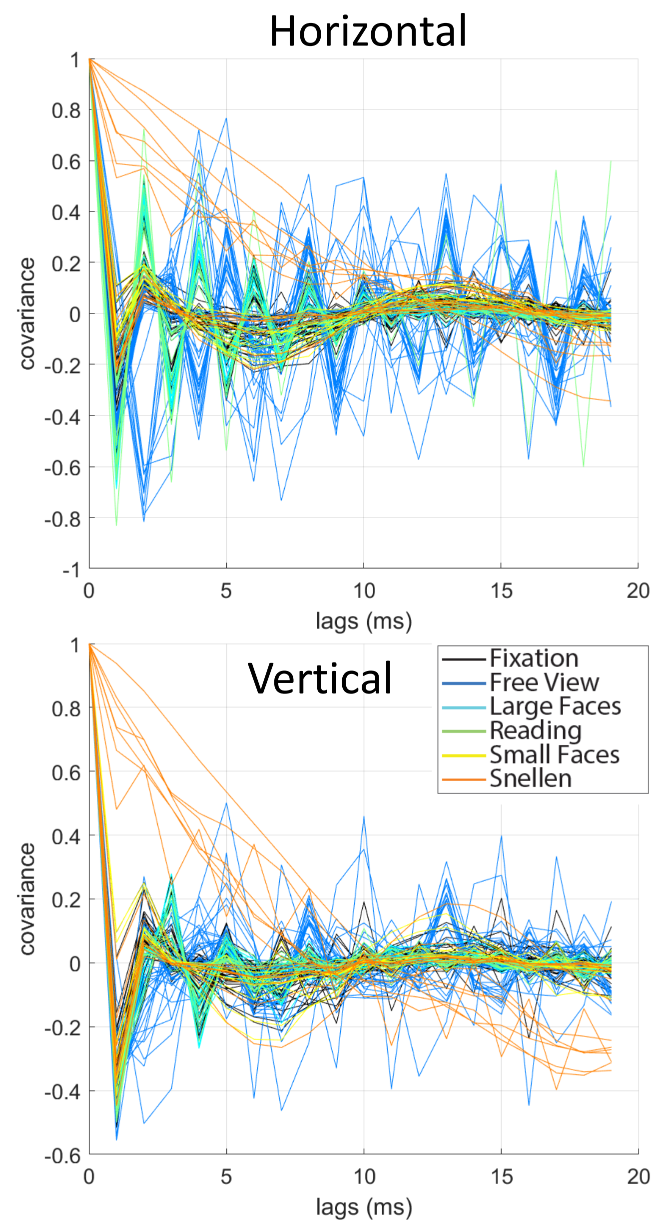


By definition, covariance of fractional Gaussian noise (difference between time samples) is characterized by

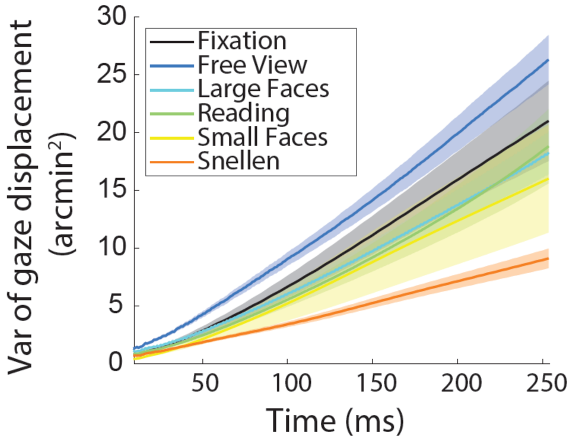
$$cov(X_i, X_{i+k})$$
$$= \frac{1}{2}(|k+1|^{\frac{H}{2}} - 2|k|^{\frac{H}{2}} + |k-1|^{\frac{H}{2}})$$

Temporal correlations





Temporal correlations



Brownian Motion(BM):

$\langle r^2 \rangle = 4Dt$

Fractional Brownian Motion (fBM):

$\langle r^2 \rangle = 4Dt^H$

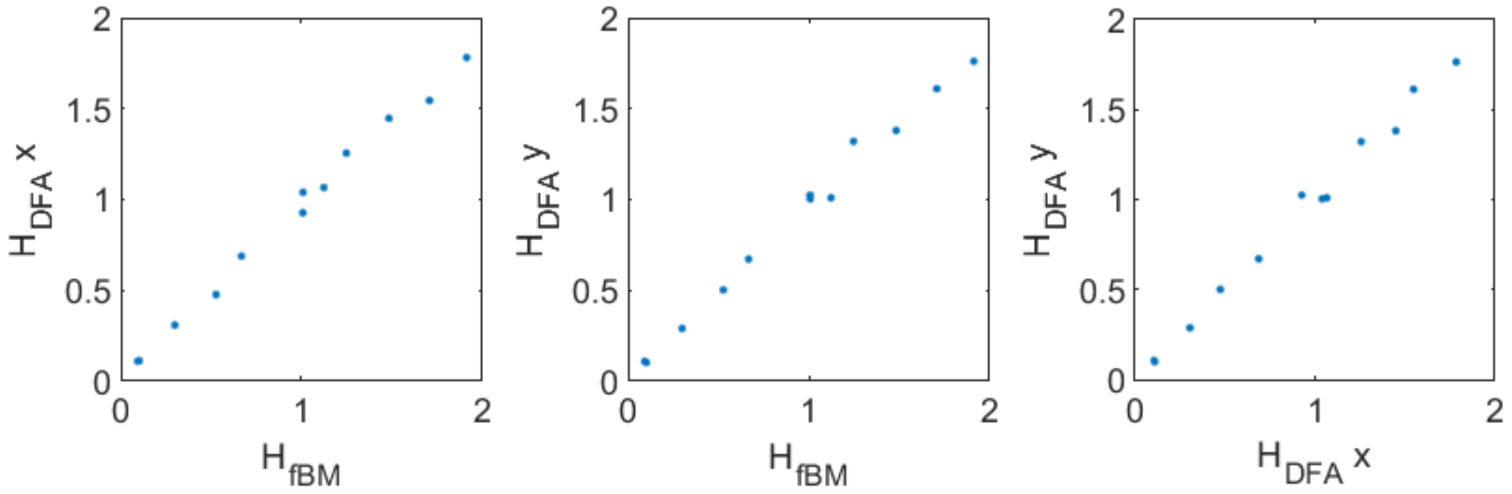
$H = 1 \rightarrow$ Brownian Motion

1. Examine covariance of step size across time
2. Estimate H (by regression or DFA)

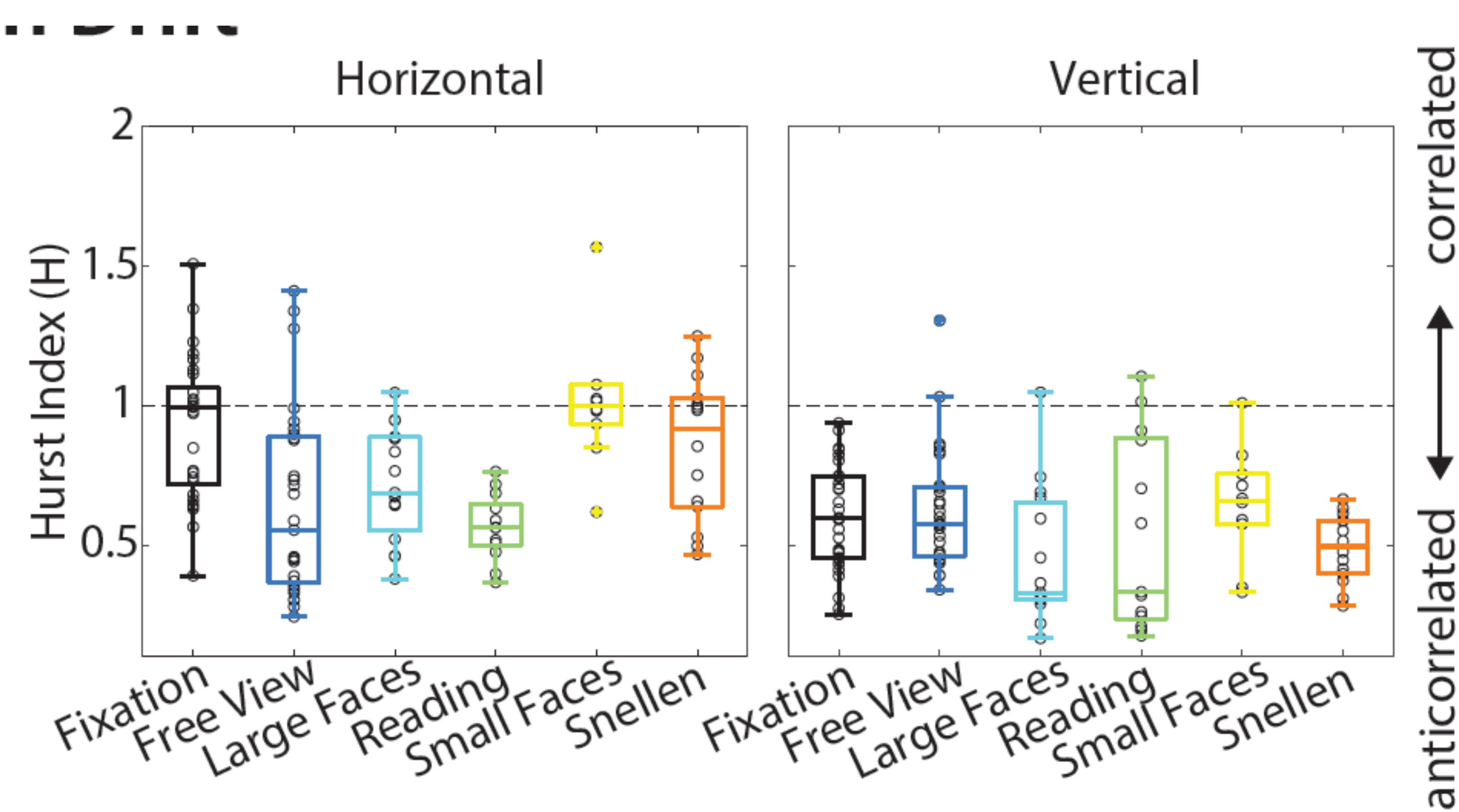
Temporal correlations: estimating Hurst index

- H_{fBM} fit by regression to variance of displacement
- H_{DFA} fit by detrended fluctuation analysis

Estimations on simulated fBM traces:



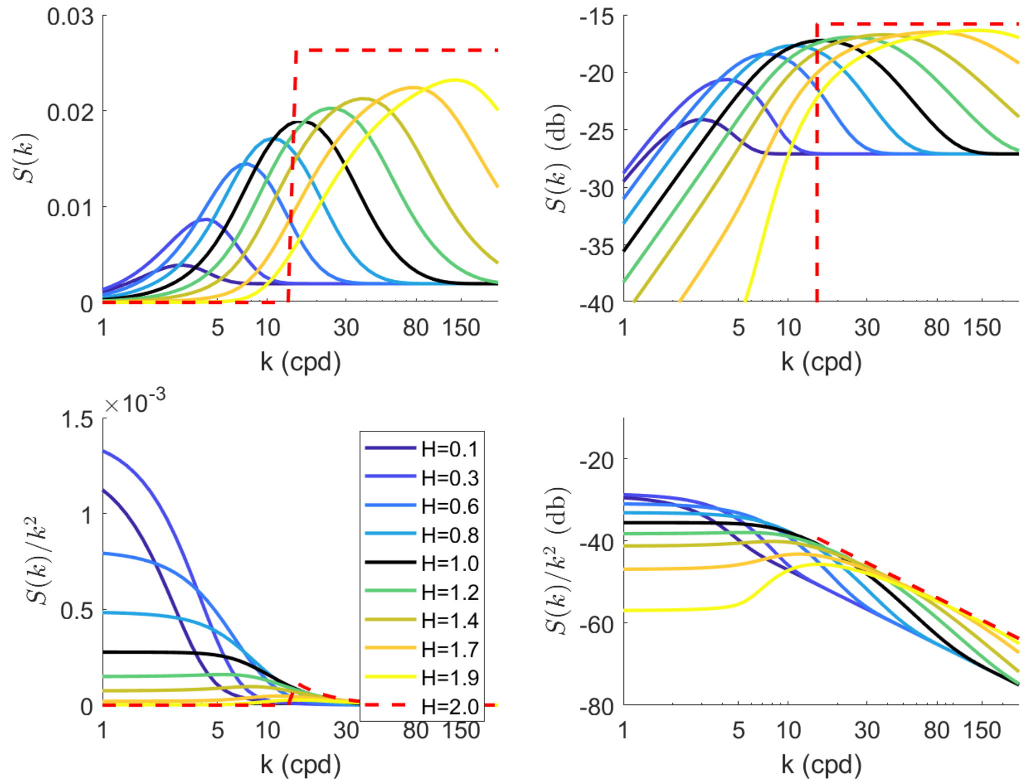
Temporal correlations



Power spectra of fBM

Numerical PSD
(see report for details)
Integrate Q(*k*, *f*; *D=2C*
H) over 2<*f*<40 Hz

- Larger *H*: higher critical frequency, but filters out low spatial frequencies



Task-dependent control of drift

- Do humans alter drift by task?
  - Is this done to optimize spatial information in the visual input?
  - Are there ways to improve vision based on these models?
- Can humans control D and H?
  - Varying both together alters the spatial frequency content of visual input, but H varies how space is explored
  - Does it just depend on the inertia of the eye following saccades (which are much less frequent in high acuity tasks)