



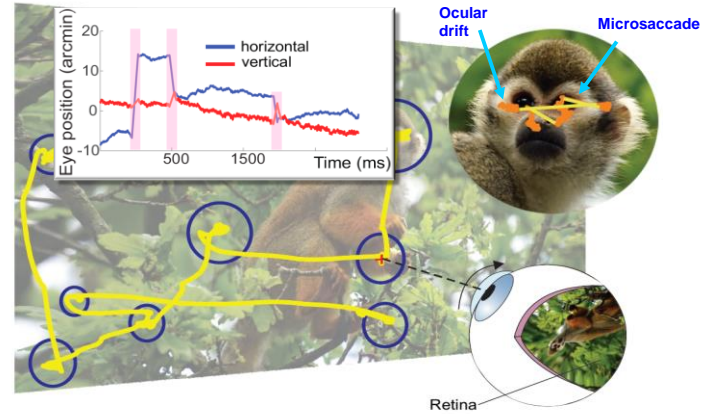
# Representing Space with Jittering Eyes

Michele Rucci

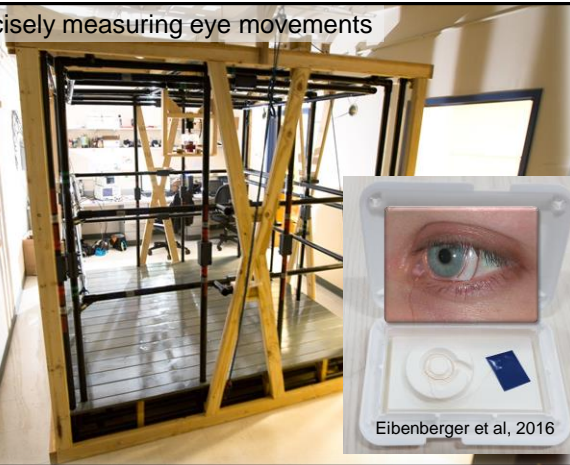
Department of Brain & Cognitive Sciences  
Center for Visual Science  
University of Rochester



## Our eyes are never at rest



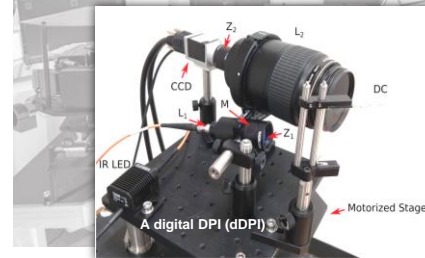
## Precisely measuring eye movements



## Controlling retinal stimulation

### Dual-Purkinje-Image (DPI) eye-tracker

Maximum delay: two frames  
(6 ms at 360 Hz; typical delay 4 ms)

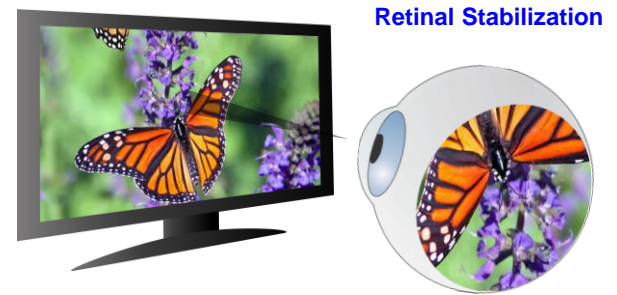


Santini et al, *Behav. Res. Methods*, 2007

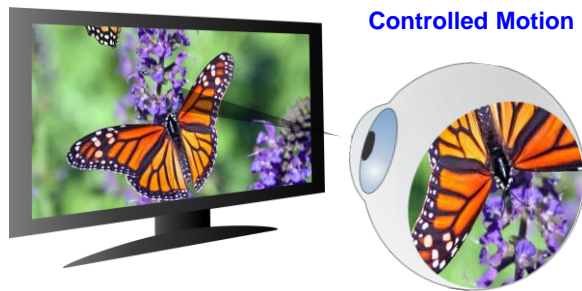
Controlling retinal stimulation



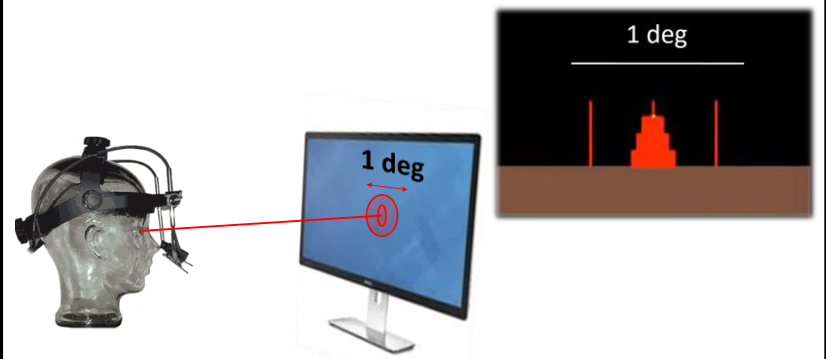
Controlling retinal stimulation



Controlling retinal stimulation

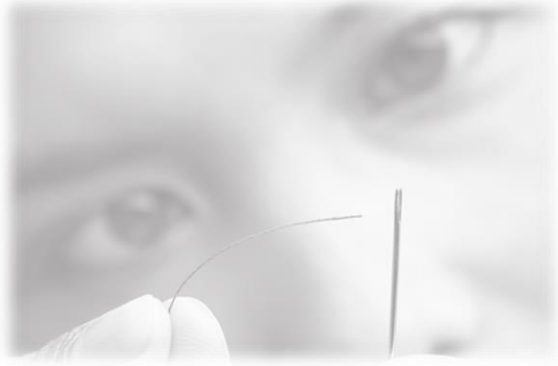


Accurate gaze control



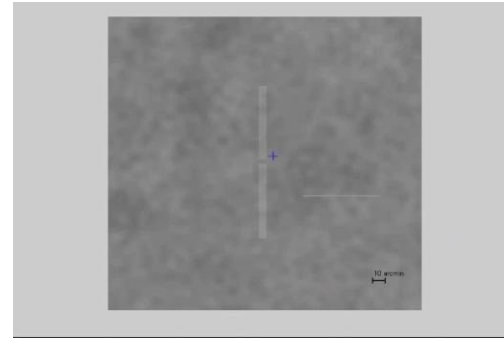
Poletti, Listorti, Rucci, *Current Biology*, 2013

### Naturalistic tasks (no enforced fixation)



### A surprising degree of control

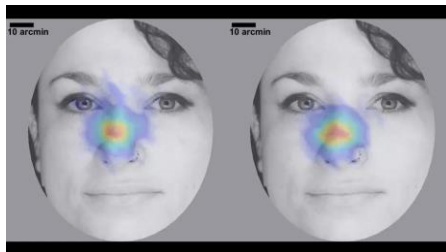
- Microsaccades precisely relocate gaze



Ko et al, *Nature Neurosci*, 2010

### A surprising degree of control

- Microsaccades precisely relocate gaze



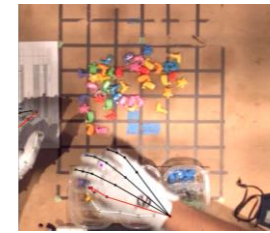
**Gaze direction  
judgement**

**expression  
judgement**

Shelchkova et al, *PNAS*, 2019

### A surprising degree of control

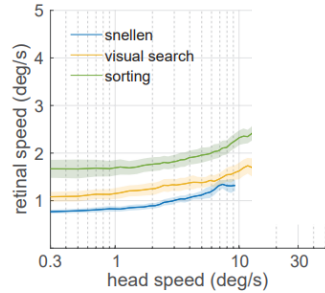
- Microsaccades precisely relocate gaze
- Ocular drifts are also controlled



Zhao et al, *in prep.*, 2022

### A surprising degree of control

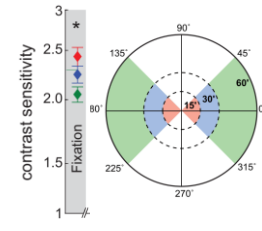
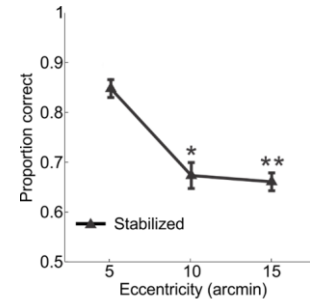
- Microsaccades precisely relocate gaze
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Zhao et al, *in prep.*, 2022

### Why such control?

- In part, to position the retinal stimulus

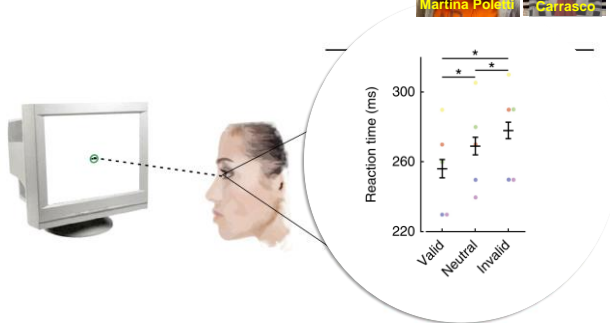


Poletti, Listorti, Rucci, *Current Biology*, 2013

Intoy, Mostofi, Rucci, *PNAS*, 2021

### Why such control?

- In part, to benefit from attentional modulations

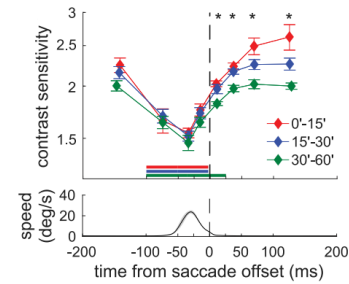


Poletti et al., *Nature Neurosci.* 2017

### Why such control?

- In part, to benefit from extraretinal modulations

#### Dynamics of contrast sensitivity around microsaccades

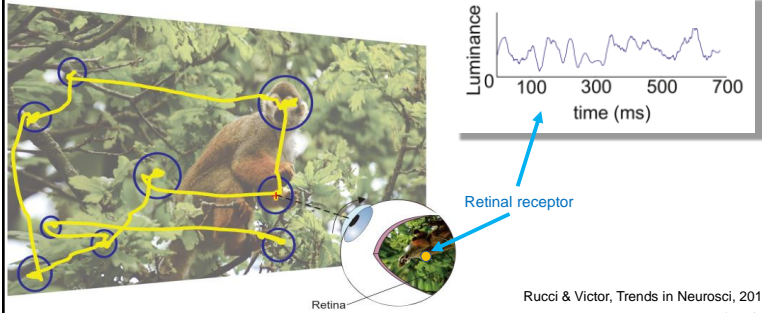


Intoy et al, *PNAS*, 2021

### Why such control?

- In part, to control luminance modulations

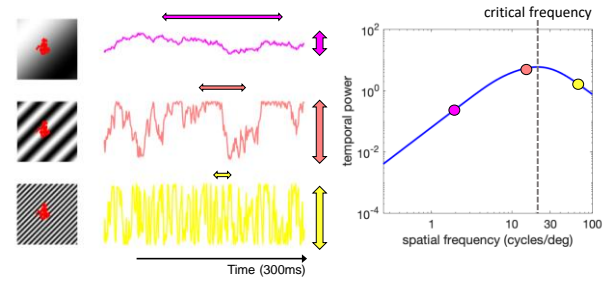
#### A spatiotemporal reformatting



Rucci & Victor, Trends in Neurosci, 2015  
 Rucci, Ahissar & Burr, Trends in Cog Sci, 2018

### Ocular Drift

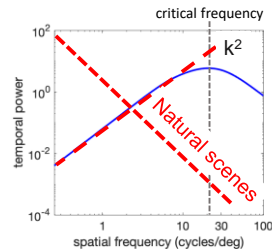
The space-time conversion from drift acts as a spatial filter



Kuang et al, Current Biology, 2012

### Ocular Drift

The space-time conversion from drift acts as a spatial filter that pre-processes information efficiently

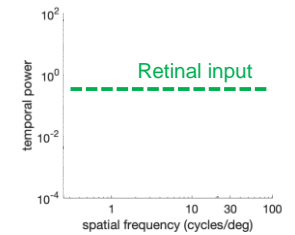


Kuang et al, Current Biology, 2012

### Ocular Drift

The space-time conversion from drift acts as a spatial filter that pre-processes information efficiently

**Equalization (or whitening):**  
 A standard technique in signal processing to improve efficiency of representations and signal transmission.

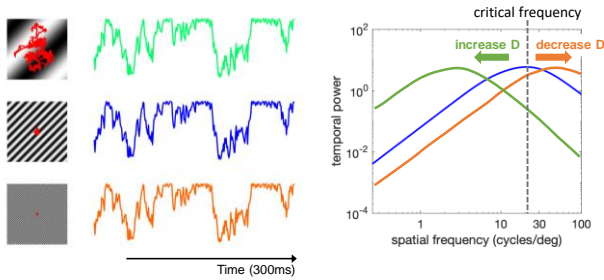


A form of matching between the luminance modulations from ocular drift and the natural visual world

Kuang et al, Current Biology, 2012

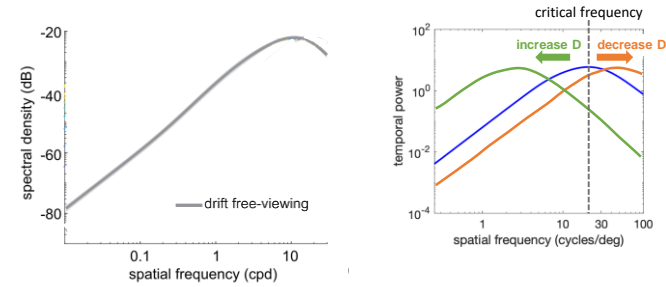
### Ocular Drift

The space-time conversion from drift acts as a spatial filter that pre-processes information efficiently and **could be flexibly tuned via motor control**



### Ocular Drift

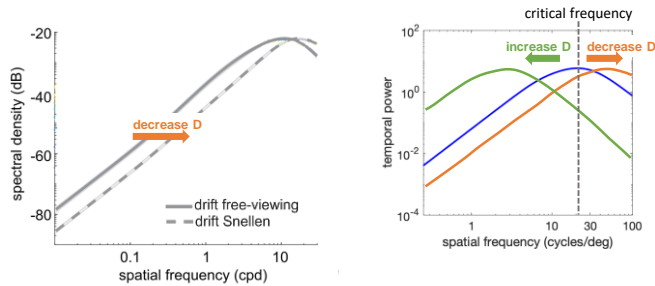
The space-time conversion from drift acts as a spatial filter that pre-processes information efficiently and **could be flexibly tuned via motor control**



Intoy & Rucci, *Nature Communications*, 2020

### Ocular Drift

The space-time conversion from drift acts as a spatial filter that pre-processes information efficiently and **could be flexibly tuned via motor control**



Intoy & Rucci, *Nature Communications*, 2020

Are these modulations important?

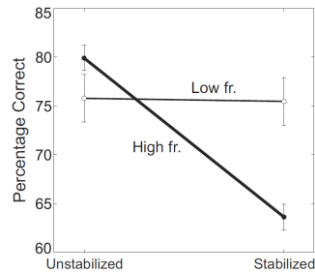
### Perceptual consequences

- **Drift modulations:** enhance fine pattern vision (*Rucci et al, Nature 2007; Ratnam et al, JoV 2017*)

High Frequency



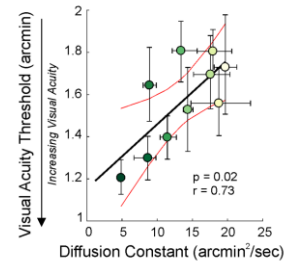
Low Frequency



Rucci, Poletti, Iovin & Santini, *Nature*, 2007

### Perceptual consequences

- **Drift modulations:** enhance fine pattern vision (*Rucci et al, Nature 2007; Ratnam et al, JoV 2017*)
- enhance contrast sensitivity (*Boi et al, Curr Biol, 2018; Casile et al, eLife 2019*)
- predict individual acuity limits (*Clark et al, PNAS 2022*)



Subjects with smaller drift have higher acuity

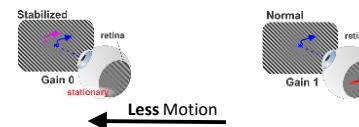


Ashley Clark

### Perceptual consequences

- **Drift modulations:** enhance fine pattern vision (*Rucci et al, Nature 2007; Ratnam et al, JoV 2017*)
- enhance contrast sensitivity (*Boi et al, Curr Biol, 2018; Casile et al, eLife 2019*)
- predict individual acuity limits (*Clark et al, PNAS 2022*)
- predict how sensitivity varies with controlled motion

### Drift luminance modulations drive visual sensitivity

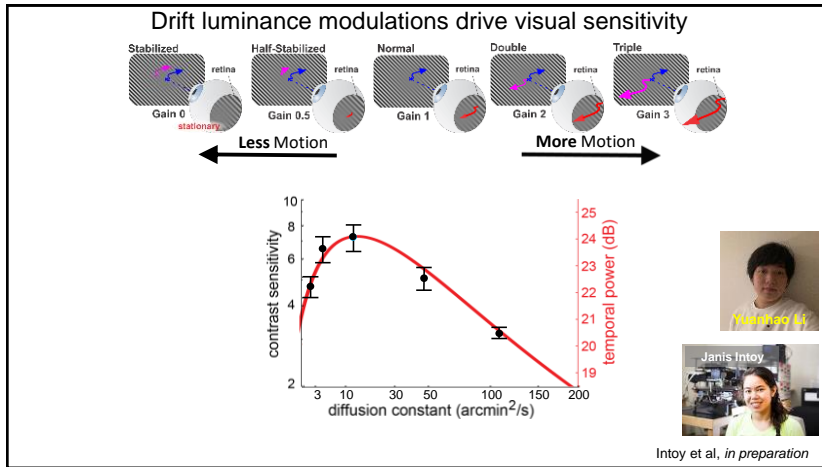


← Less Motion

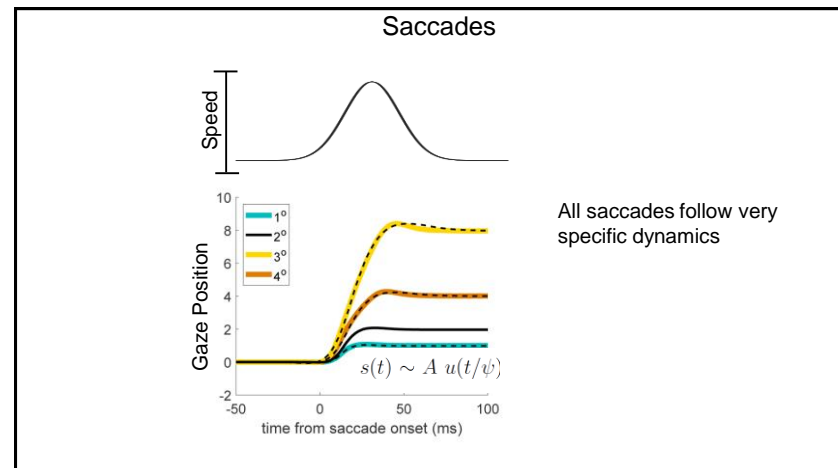
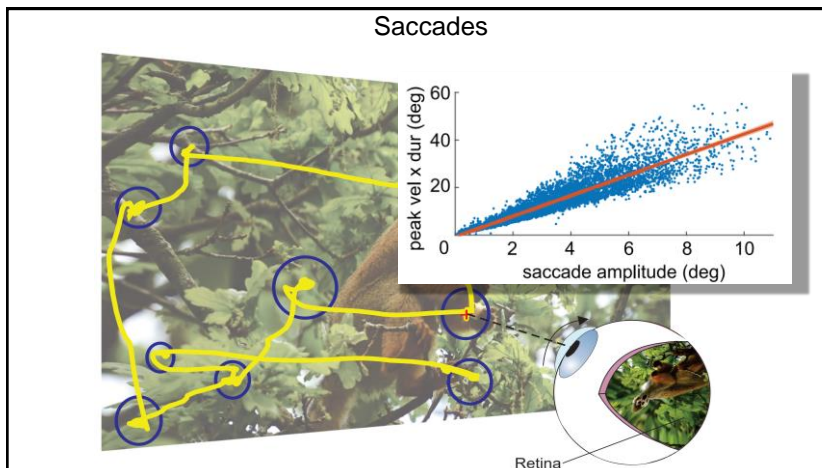
→ More Motion



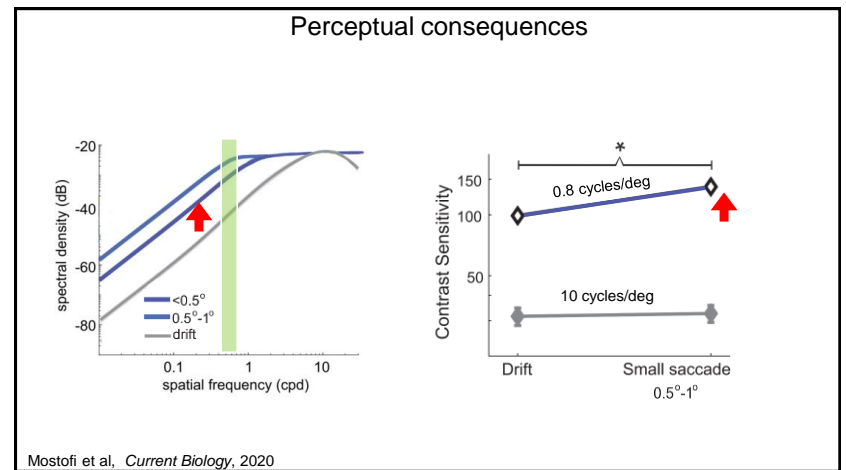
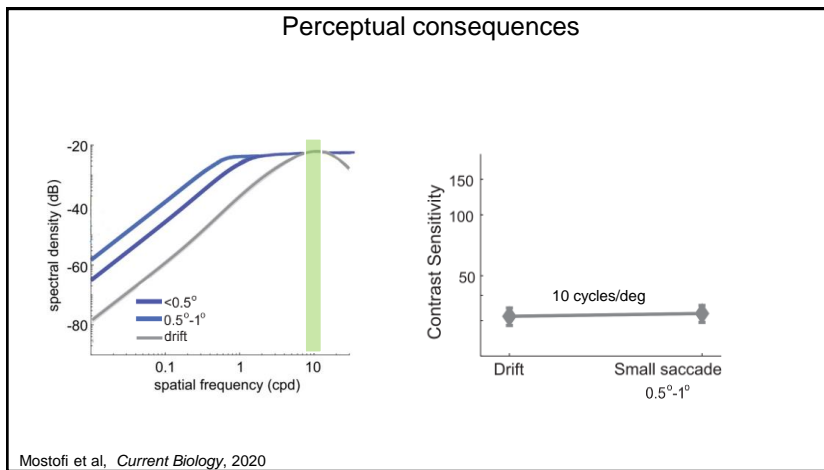
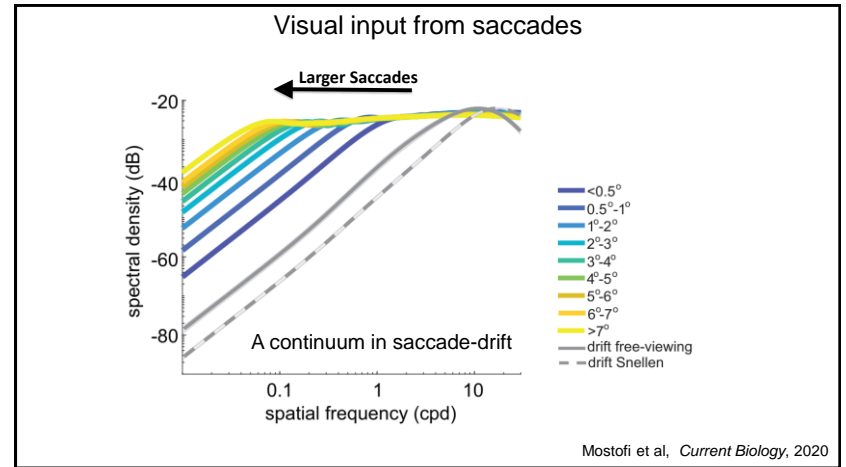
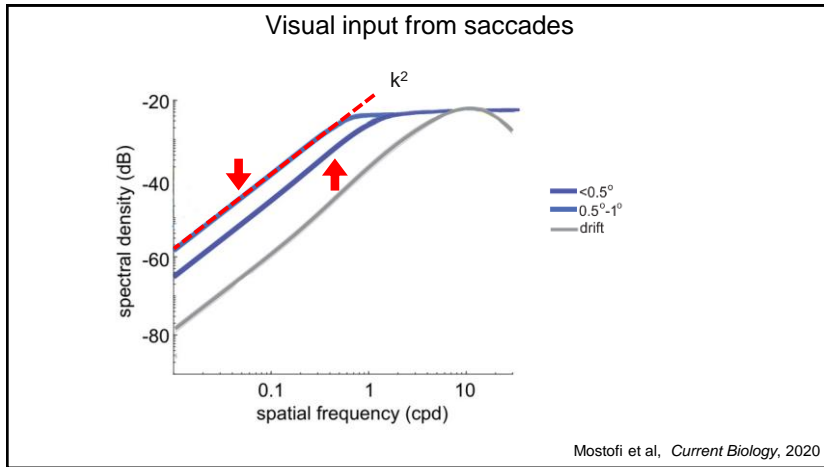
Intoy et al, *in preparation*

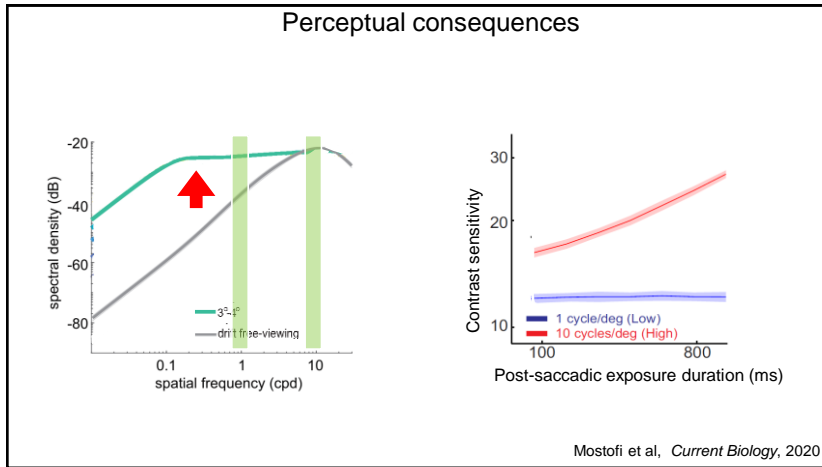


## Space-time reformatting from saccades and microsaccades







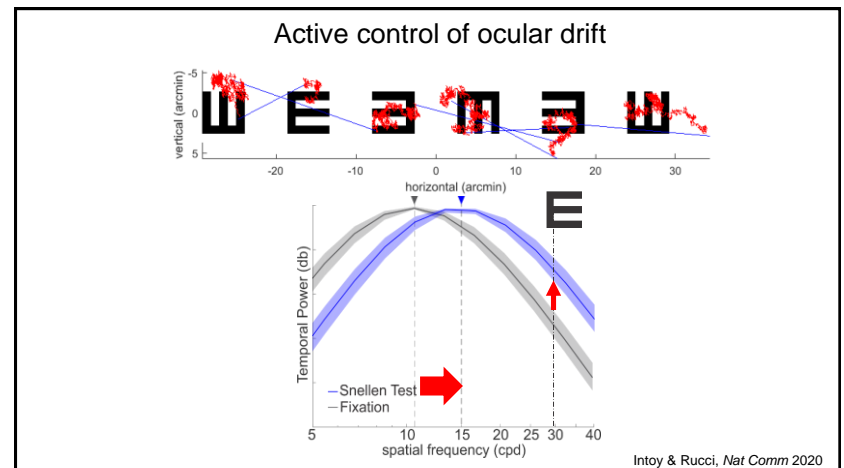
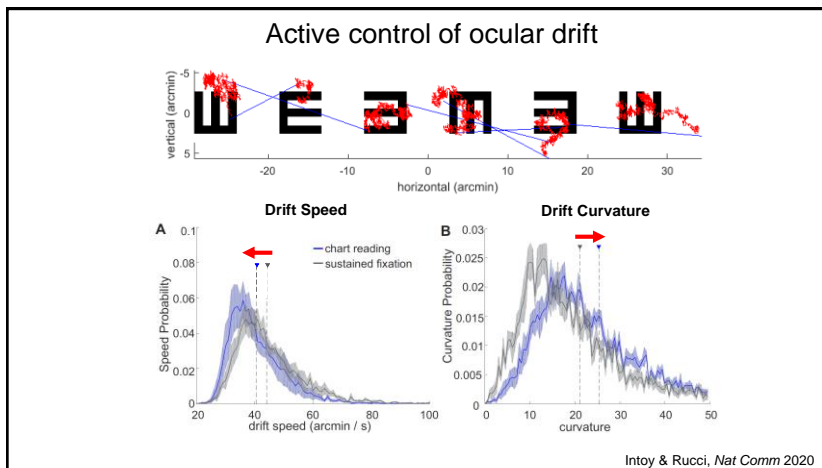


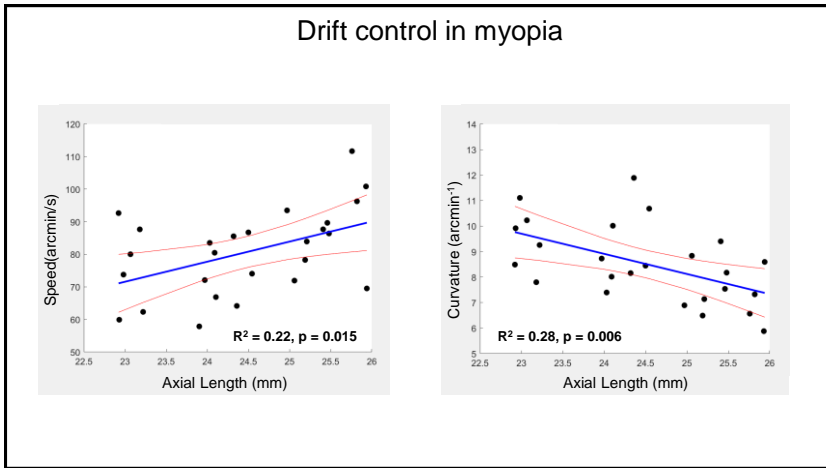
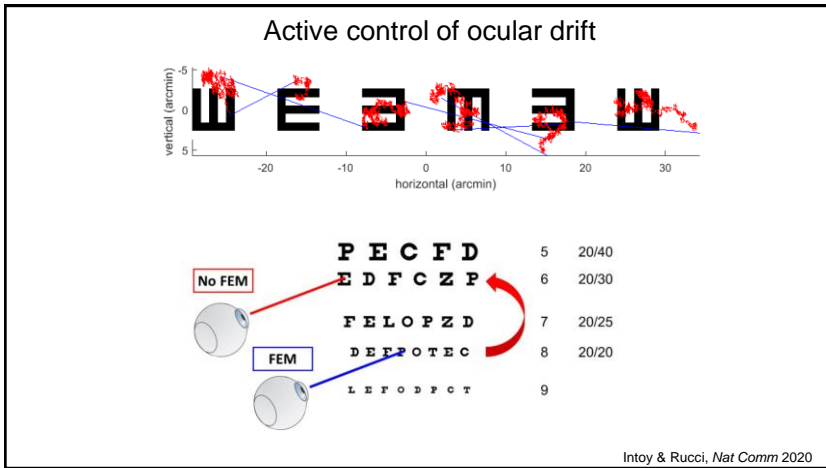
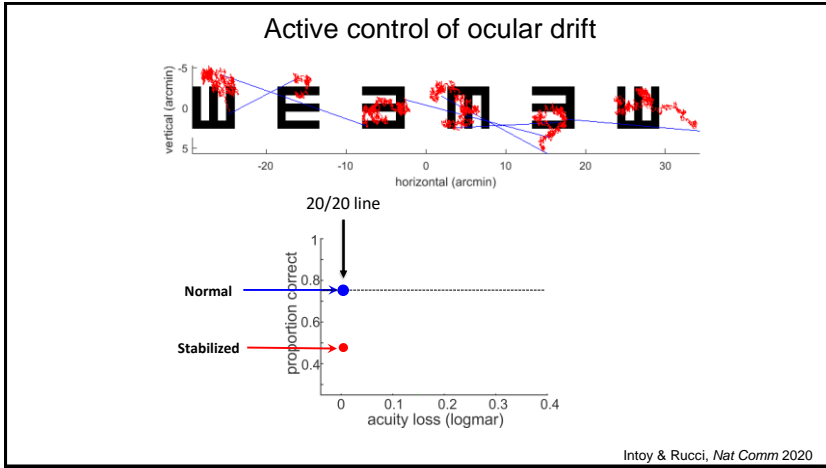
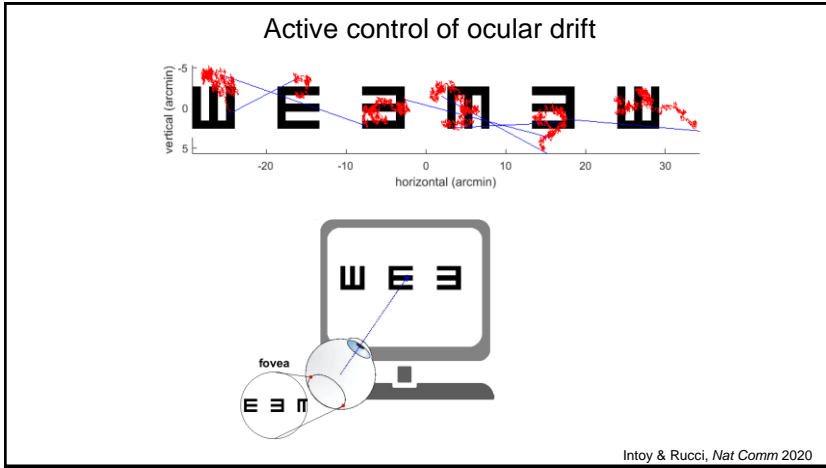
### Active control of ocular drift

W E E M E W

- Precise control of microsaccades
- Ocular drift control: drift changes relative to simple fixation.

Intoy & Rucci, *Nat Comm* 2020





## Summary

- Remarkable oculomotor control in both microsaccades and drifts.
- Eye movements continually modulate luminance signals on the retina.
- These modulations enhance selected ranges of spatial frequencies.
- Modulations from different types of eye movements form a continuum, all tuned to natural world statistics.
- Considerable and growing body of evidence showing that oculomotor modulations are part of a general strategy for encoding space in time.

