Seeing fine depth in the presence of fixational instability

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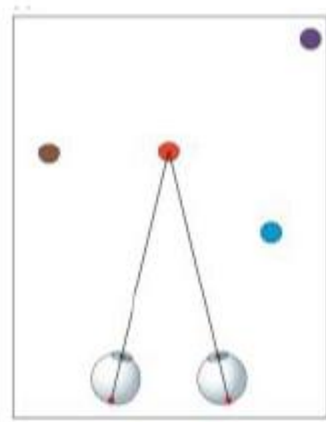
3D Vision

- Monocular cues
  - Occlusion
  - Relative size and position
  - Linear perspective
  - Motion parallax
  - Accommodation
  - …

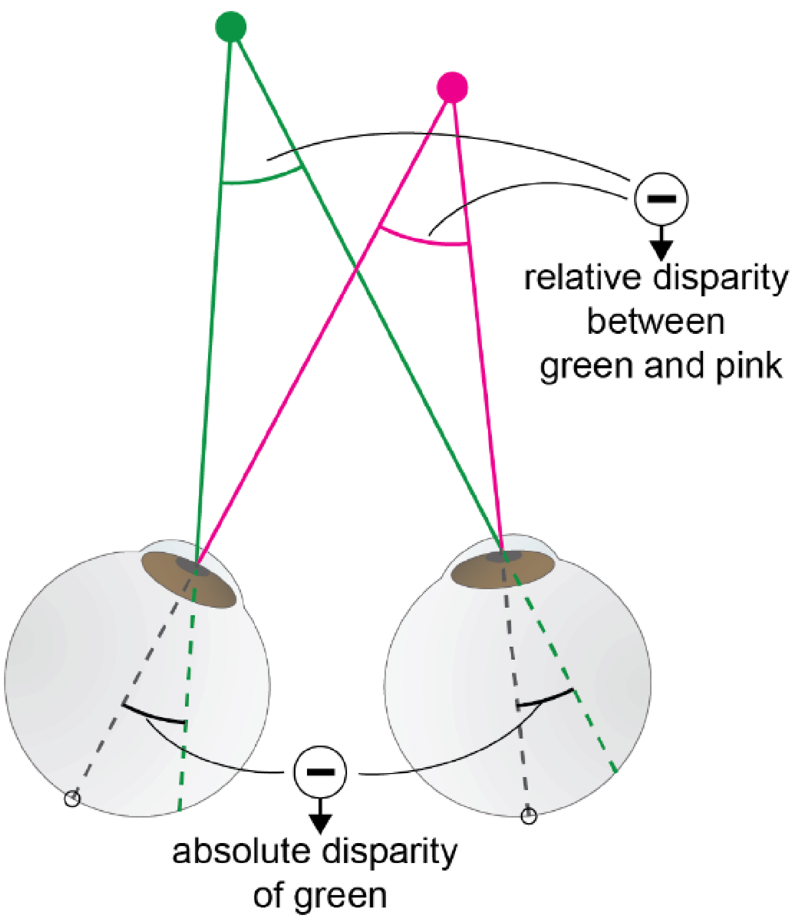
- Binocular Cue
  - Retinal disparity



Right retinal image

Left retinal image

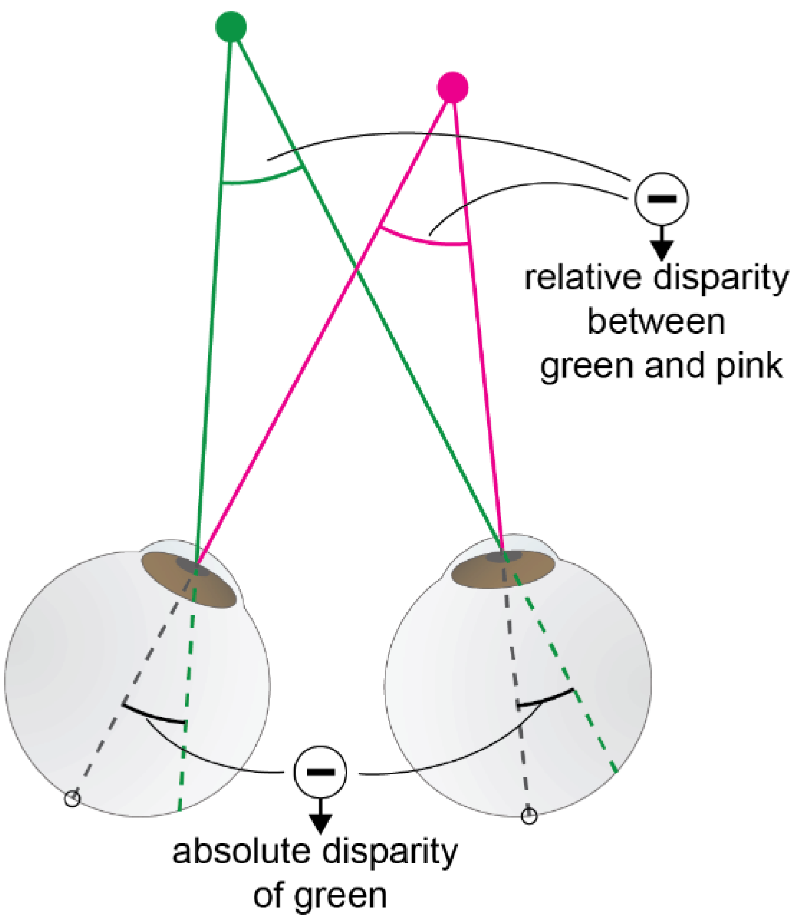
Stereopsis



Disparity → stereopsis

- **Stereopsis** is the process of extracting depth information from the different retinal images
- **Absolute disparity** (of an object) depends on where the eyes are looking.
- **Relative disparity** (the difference in absolute disparity between two objects) does not depend on where the eyes are looking.

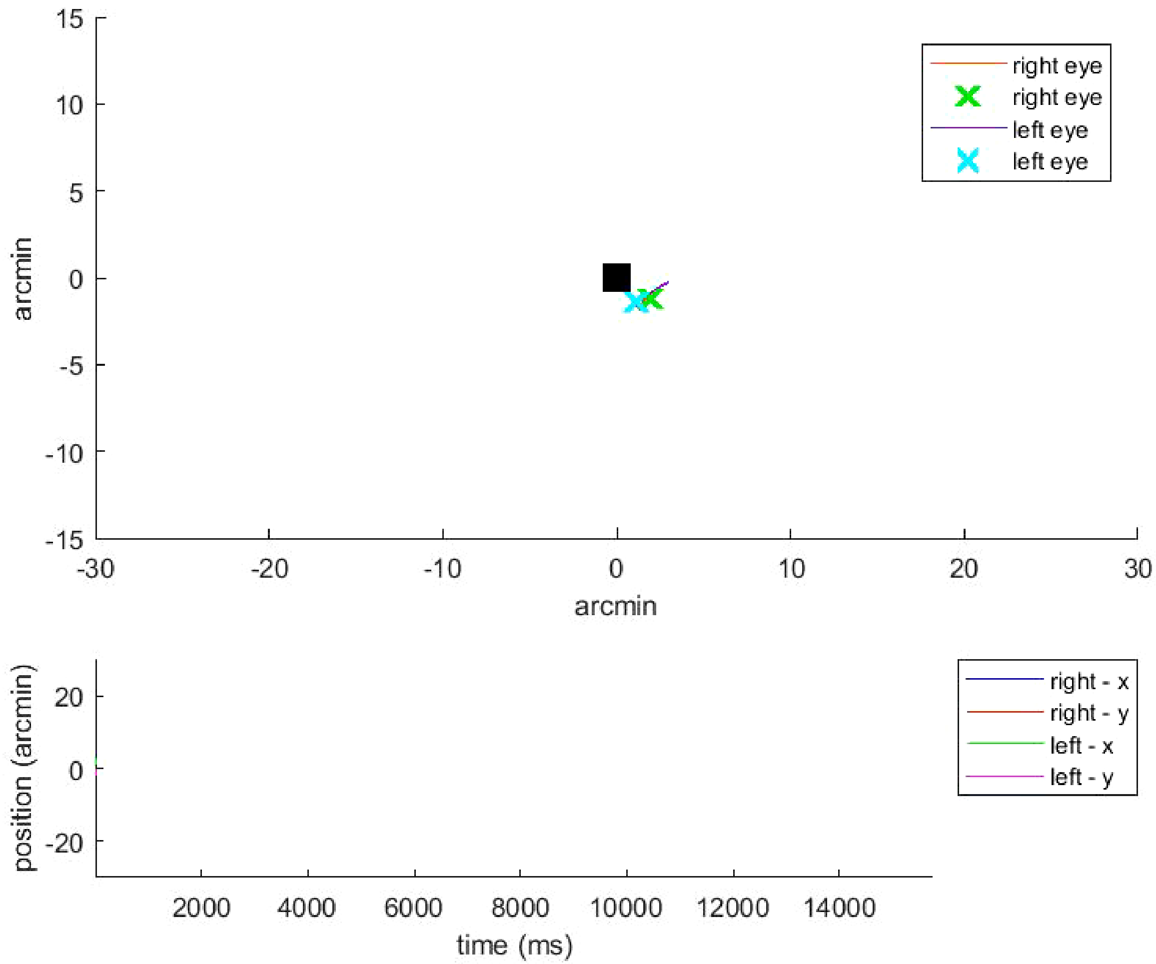
Stereopsis



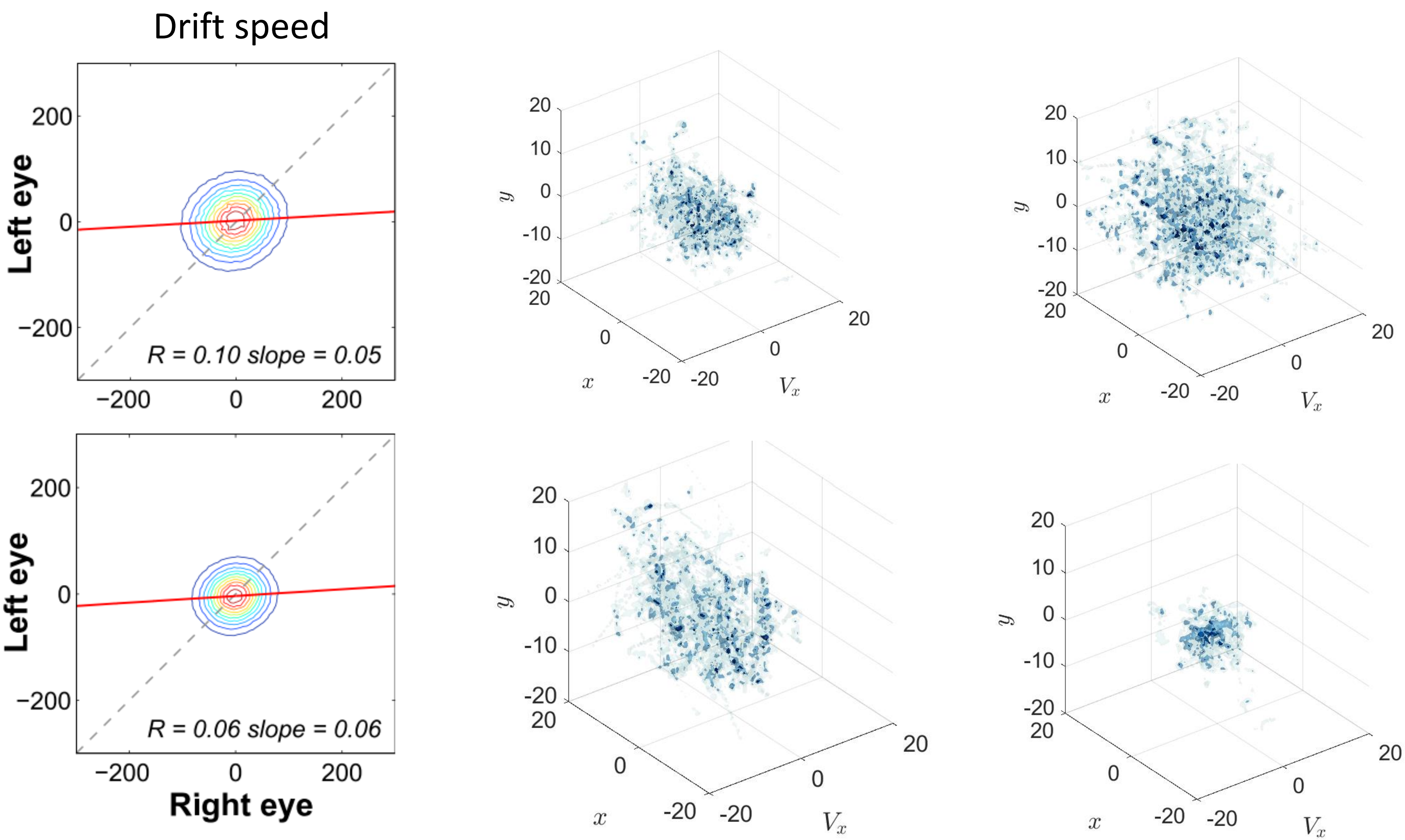
Disparity → stereopsis

- Stereoacuity thresholds can be smaller than a single cone photoreceptor

3D fixation instability



3D fixational instability



Poletti, Aytekin & Rucci (2015)

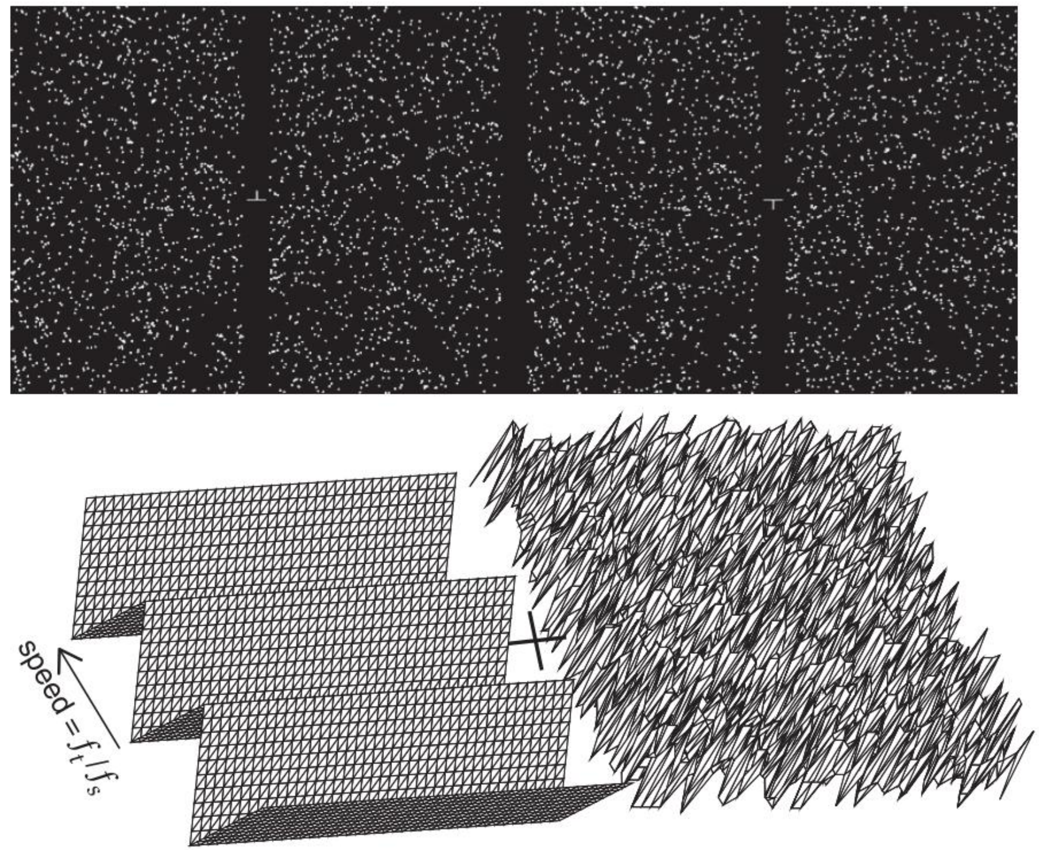
How do binocular fixational eye movements contribute to fine depth judgments?

Some Background

- Neurophysiology
  - V1 neurons are sensitive to absolute, not relative disparity (Cumming & Parker, 1999)
  - Most V2 neurons are sensitive to relative disparity (Thomas, Cumming, & Parker, 2002)
- Humans use relative disparity
  - Stereoacuity is impaired when targets are presented sequentially (Westheimer, 1979)
  - Uniform changes in absolute disparity do not give motion-in-depth percept (Erkelens & Collewjin, 1985ab; Regat et al, 1986)
- Human and neuronal spatiotemporal sensitivity to disparity modulations (next slides)

Limits of Stereopsis in Space-Time

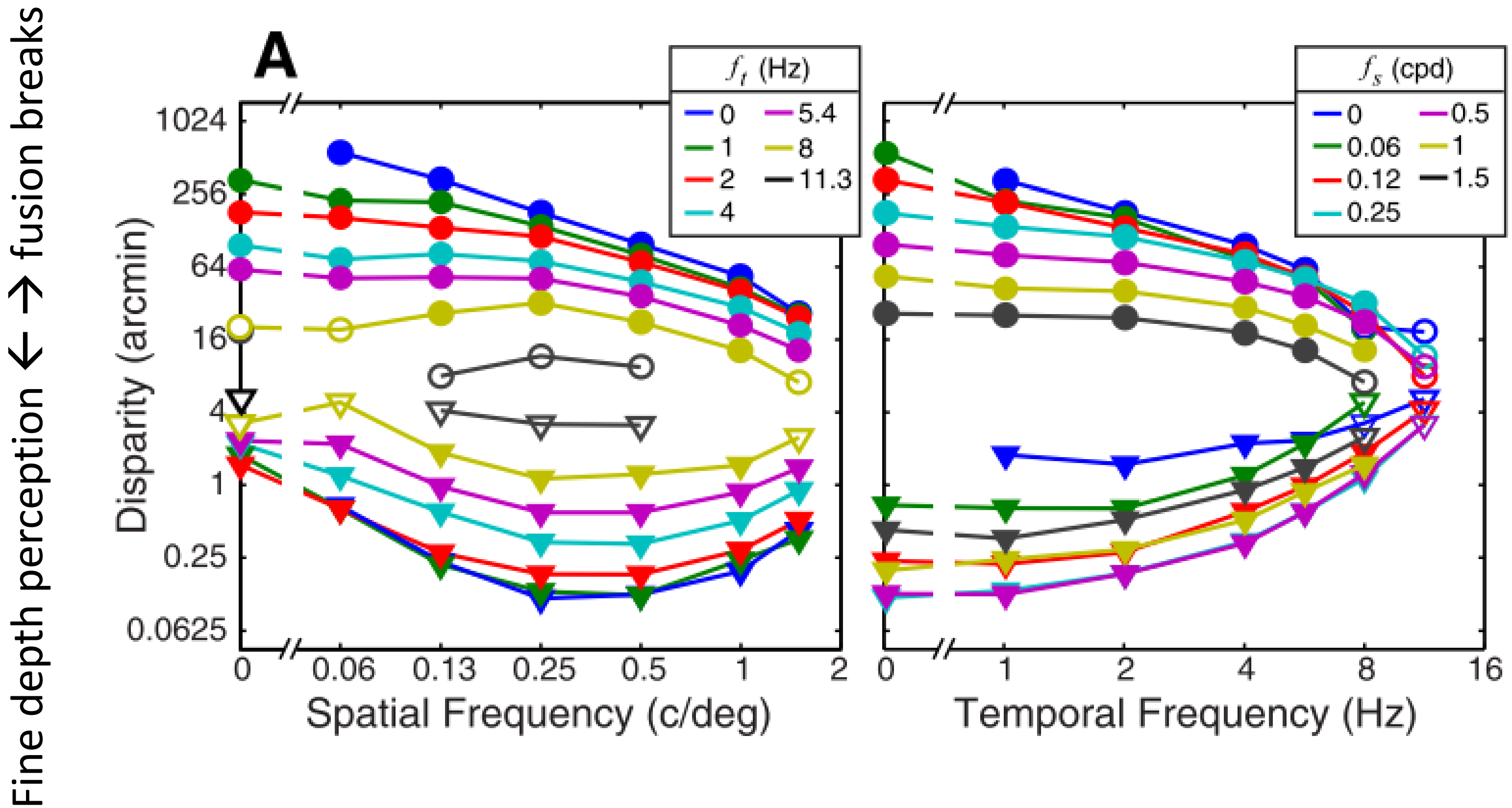
- Random dot stereogram (RDS)
- Traveling triangular wave corrugation embedded in noise
- Task: report which side (left or right) contained signal stimulus
- Measure disparity amplitude thresholds for different spatial and temporal frequencies



Kane, Guan, & Banks (2014)

Limits of Stereopsis in Space-Time

Humans are sensitive to low spatial and temporal frequencies ….



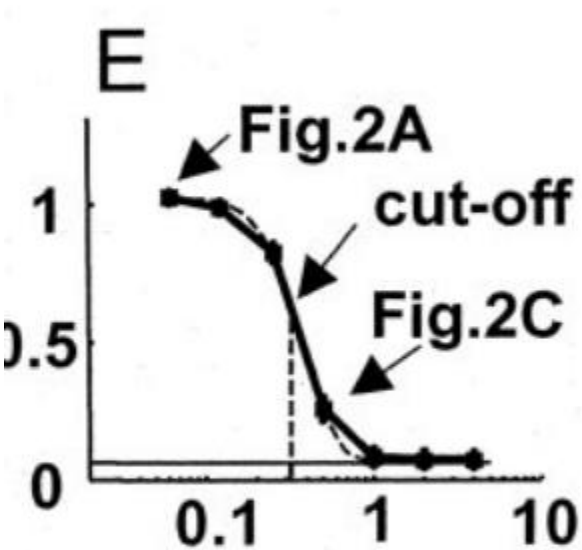
Kane, Guan, & Banks (2014)

V1 responses to absolute disparity

… and so are V1 neurons

Travelling sinusoidal corrugations (RDS)

Response strength

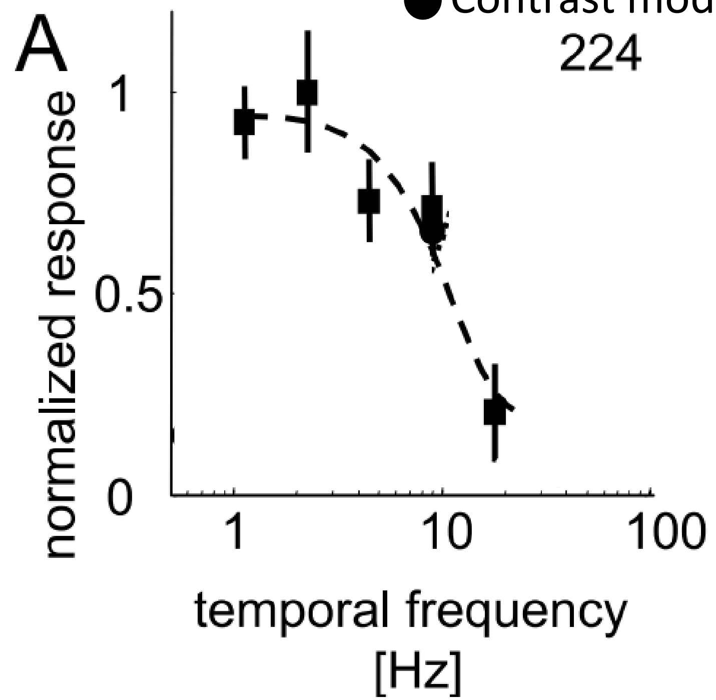


Corrugation frequency (cpd)

Nienborg et al (2004)

■ Disparity modulation

● Contrast modulation



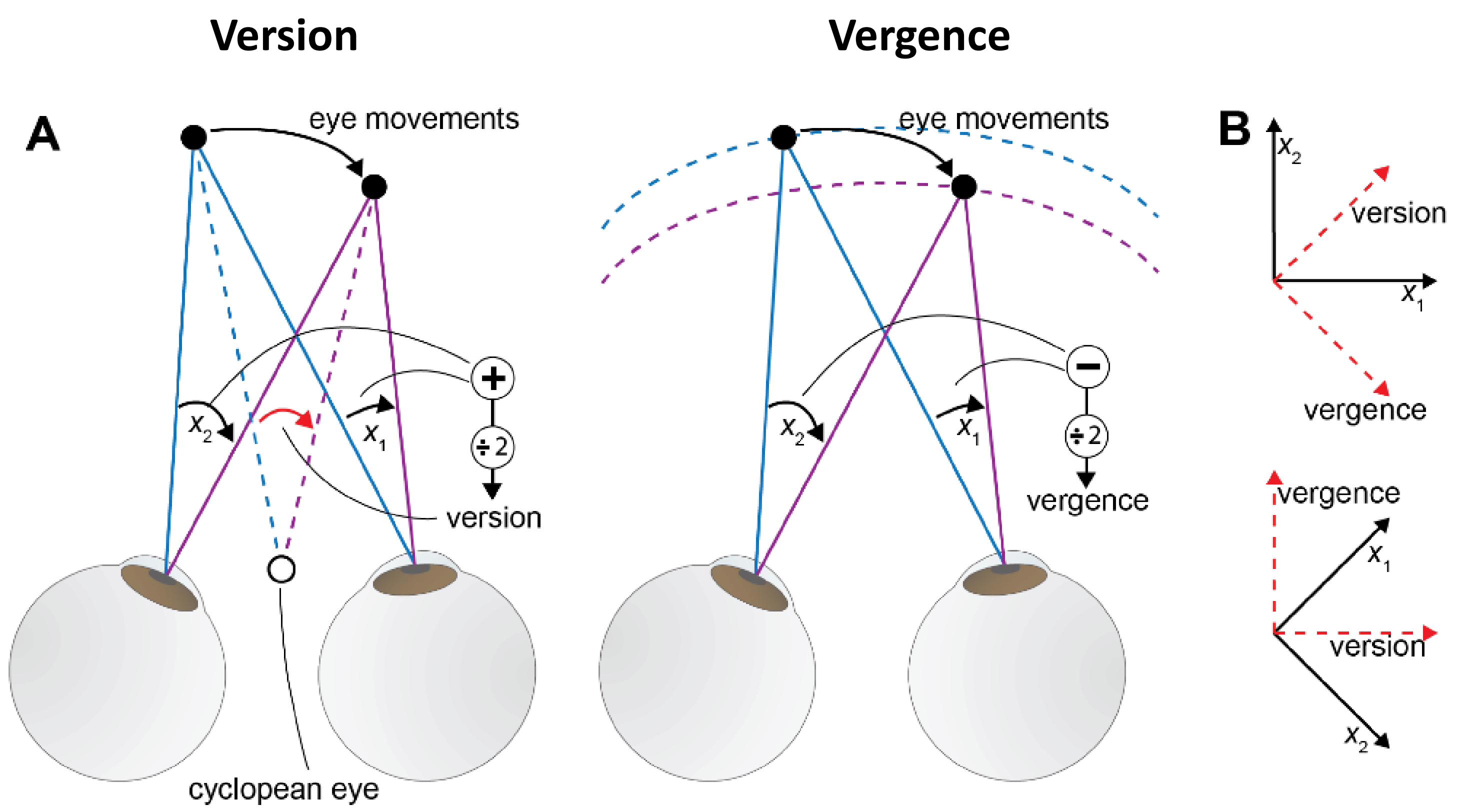
Nienborg et al (2005)

How do binocular fixational eye movements contribute to fine depth judgments?

1. Pioneering studies showed **no effect of FEM** on stereoacuity (Shortess & Krauskopf, 1961)
2. Due to preference for slow modulations, FEM could **impair fine depth judgements**.
3. As in the luminance domain, FEM could provide disparity modulations that **benefit fine depth judgments**.

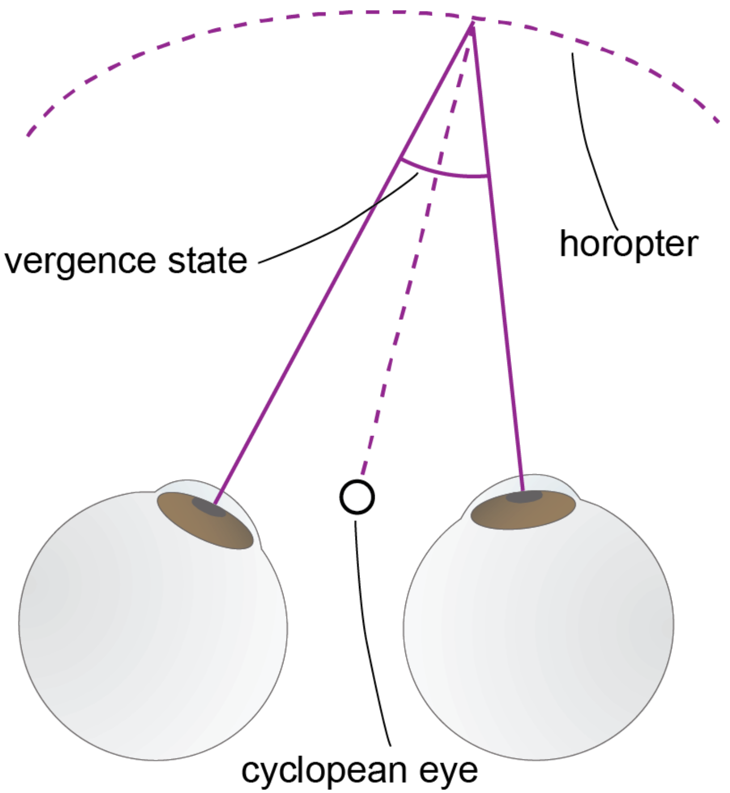
Binocular Eye Movements

Transform eye movements from [eye1, eye2] coordinate system to [version, vergence]

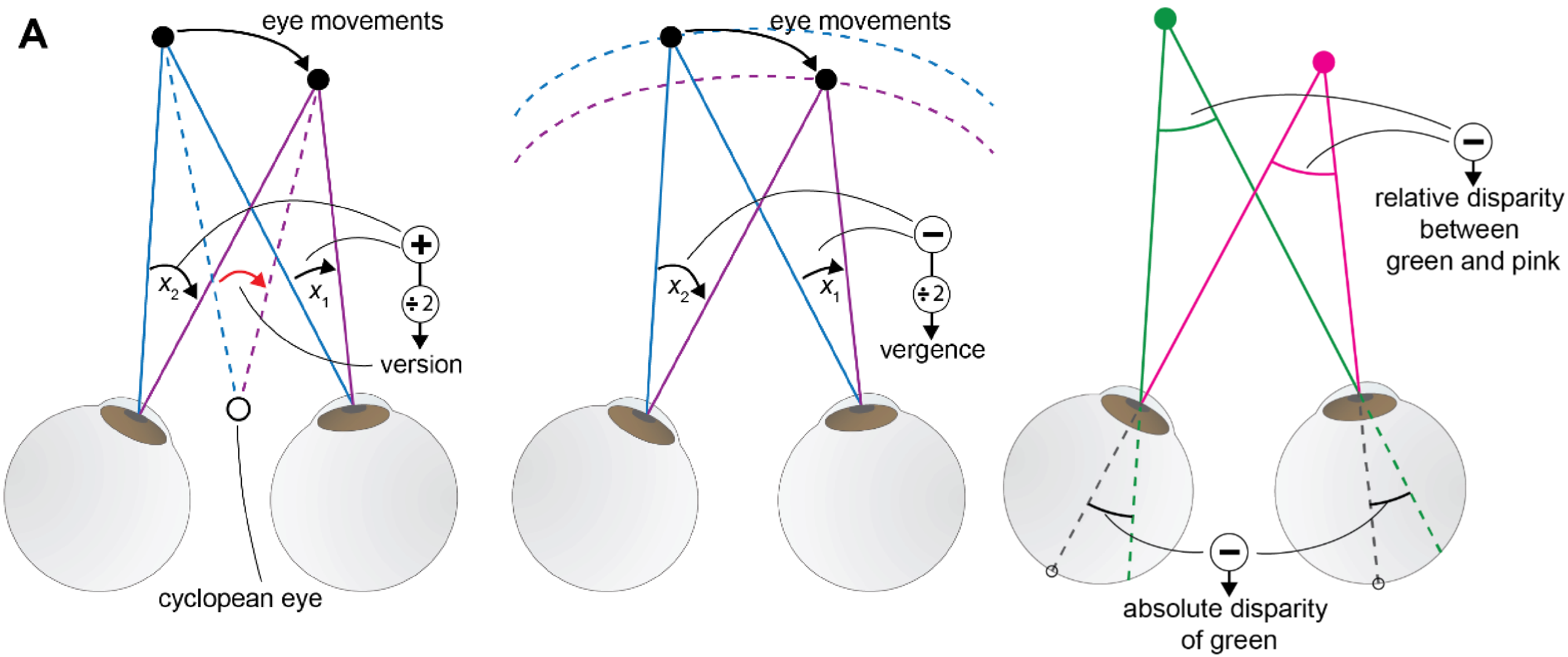


Horopter

- All points in space whose images fall on corresponding points of the retinas of the two eyes (points with zero absolute disparity)
- Vergence state is maintained when eyes move to different point on horopter



Relationship to Retinal Disparity

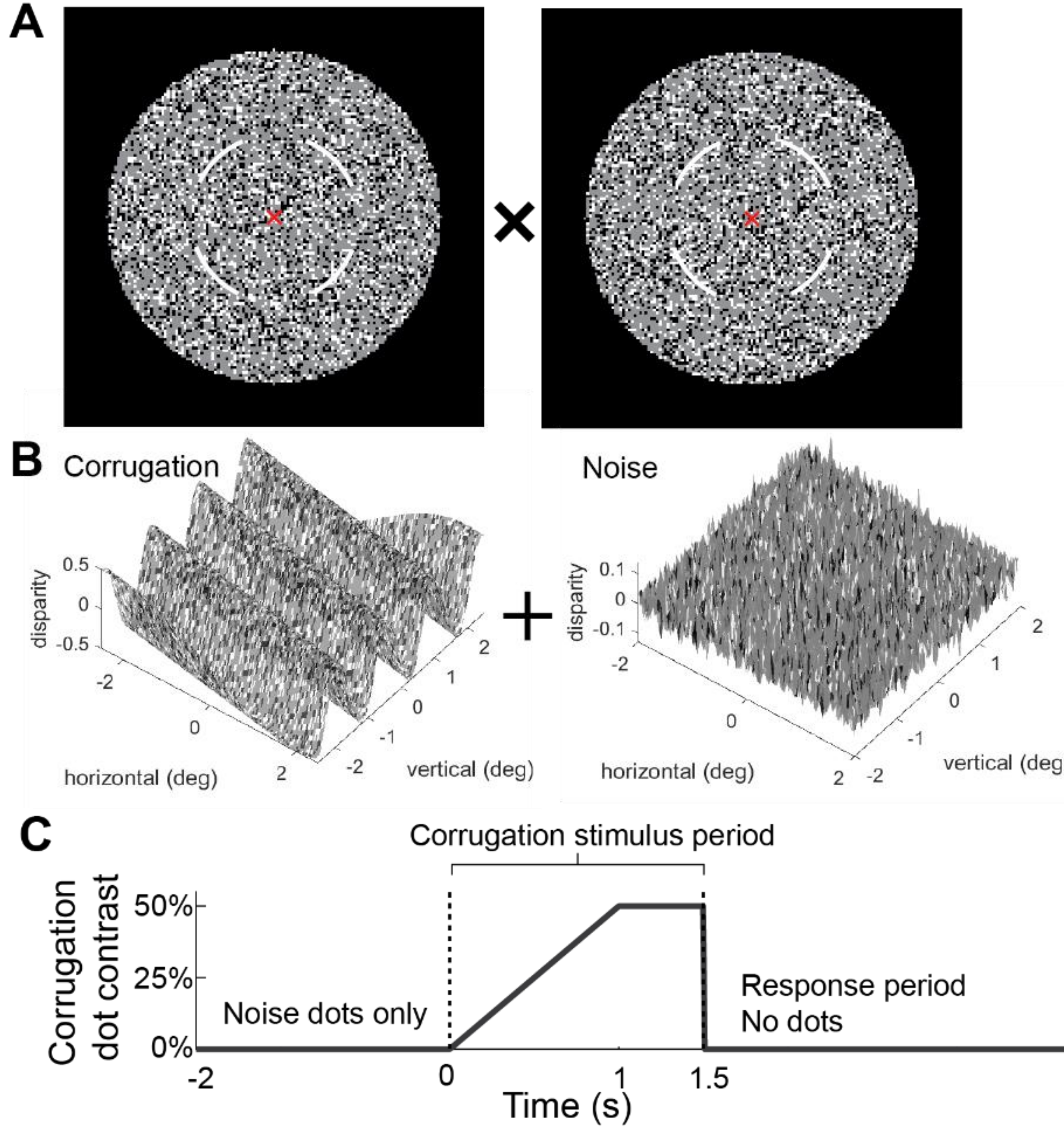


- A pure version movement shifts gaze along the horopter.

- Vergence eye movement results in change in absolute vergence of objects
- The change in vergence is equivalent to the relative disparity between the two fixated locations.

Stimulus

- 1 cpd sinusoidal corrugation (±10° from horizontal) embedded in noise
- Disparity amp. 1 or 3 arcmin by subject
- 20% dot density (black and white)
- Noisy dot disparity follows normal distribution with 2arcmin STD



Viewing Conditions

1. Normal Viewing
2. Full stabilization
   - Image stabilized independently in each eye
3. Version stabilized
4. Vergence stabilized

Conditions are interleaved (though 3 & 4 were introduced later)

Analysis Criteria

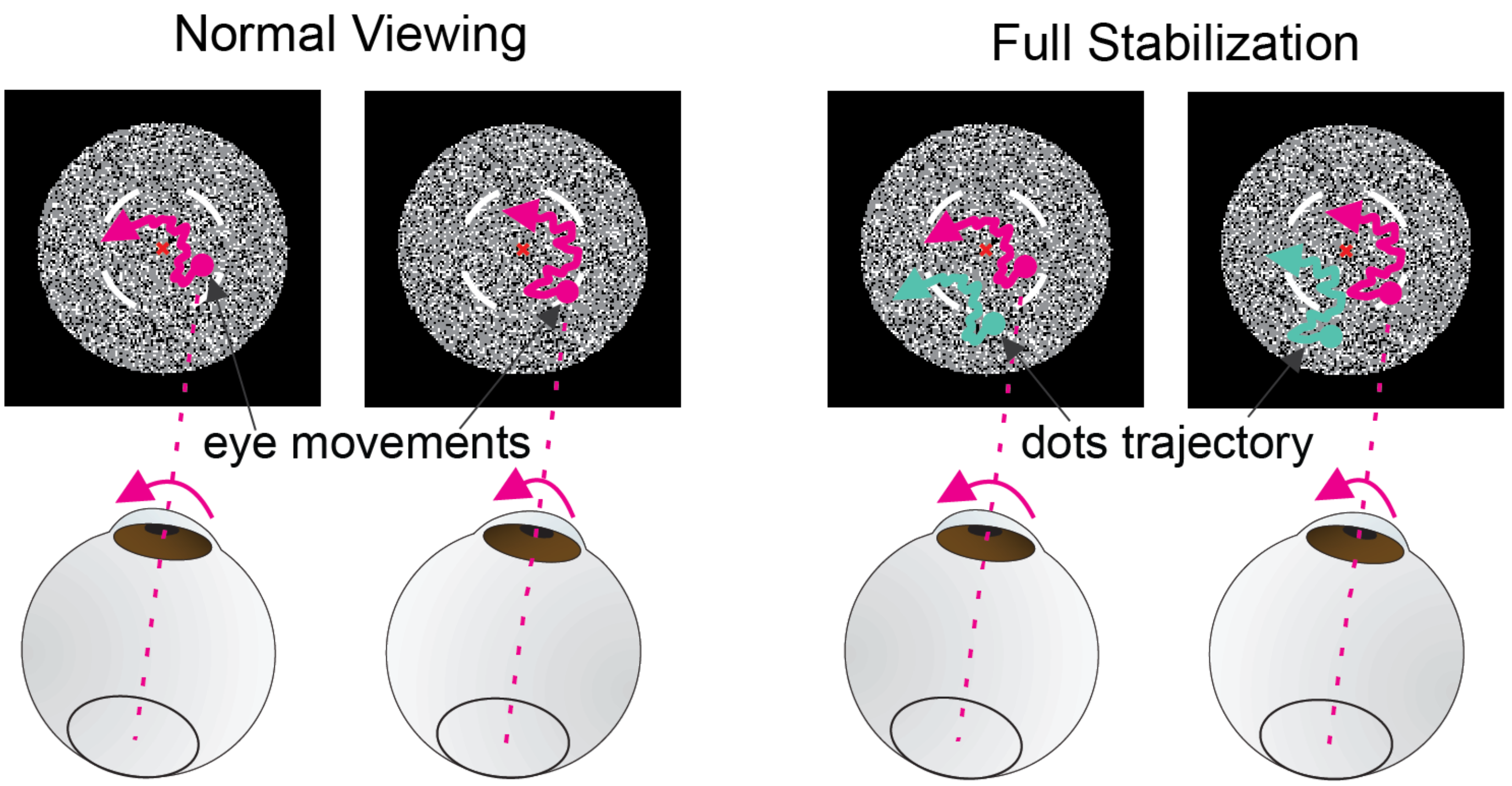
- Trials are excluded if
  - Blink or no track occurred during corrugation presentation
  - Absolute difference in eye position (vergence state) exceeded 30
  - Subject reported that fusion was broken during stimulus presentation.
- Drift-only trials are ideal for retinal stabilization, but these are proving difficult to get.

Trial Counts

	Drift Only											
	Normal			Full-Stab			Vers-Stab			Verg-Stab		
MAC	**40**	40	39	**15**	15	9						
Janis	**82**	81	74	**47**	43	34	**8**	8	8	**12**	11	11
A084	**16**	16	12	**2**	2	1						
A051	**104**	104	89	**117**	117	54	**89**	89	69	**68**	68	38
A099	**1**	0	0	**13**	6	5	**9**	3	3	**13**	9	3
A064	**13**	13	13	**14**	9	7	**19**	19	19	**14**	9	7
	Saccade allowed											
	Normal			Full-Stab			Vers-Stab			Verg-Stab		
MAC	**135**	135	132	**91**	91	55	**6**	6	5			
Janis	**131**	130	121	**108**	92	68	**18**	18	18	**16**	15	15
A084	**69**	69	48	**27**	27	15						
A051	**263**	263	239	**199**	199	102	**153**	153	120	**180**	174	98
A099	**80**	30	26	**90**	52	30	**93**	43	39	**84**	49	19
A064	**29**	29	29	**28**	19	15	**28**	28	28	**25**	17	9

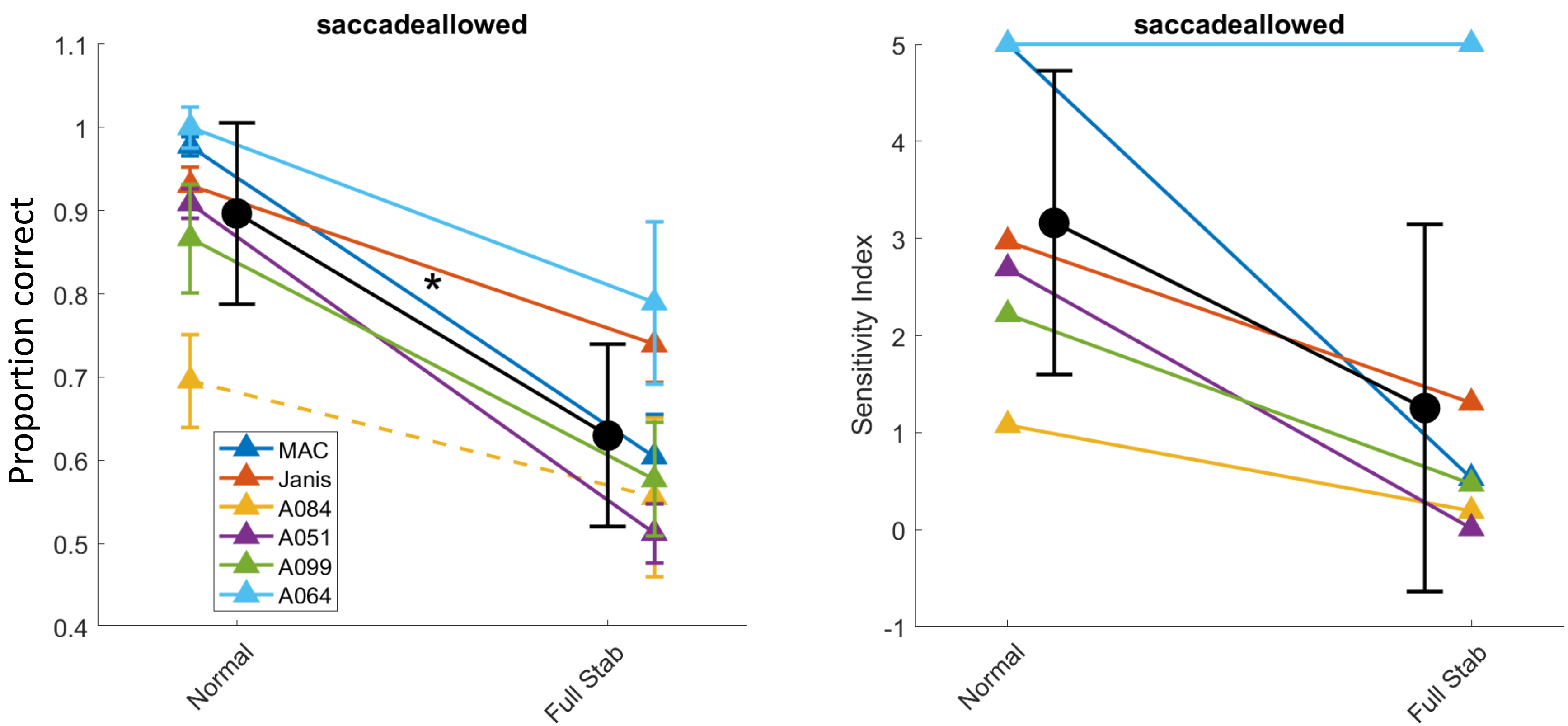
Table 1: Number of trials by type of eye movement (drift-only, microsaccades allowed, or all trials) and by stabilization condition. Numbers are total # of trials (bold face), number fused trials (normal black text), and number fused trials with correct orientation-discrimination (blue)

Normal and Full-Stabilization



- Full stabilization ideally eliminate all luminance and disparity modulations.
- Relative disparity modulations exist between stabilized and non-stabilized objects on the monitor.

Discrimination Performance

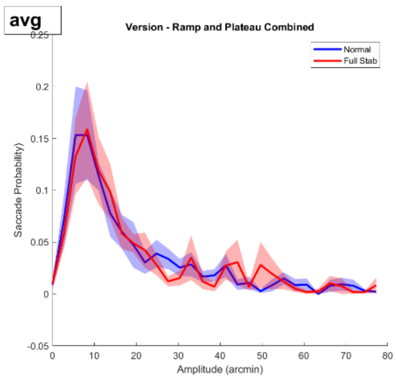


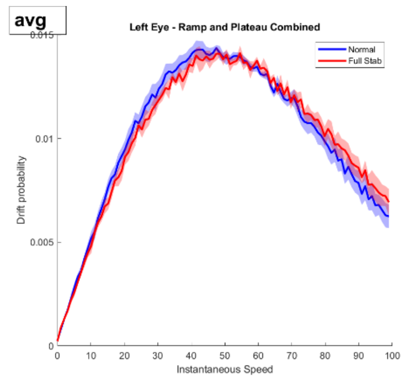
Note that sensitivity index is infinity for some subjects, plotted here with a value of 5.

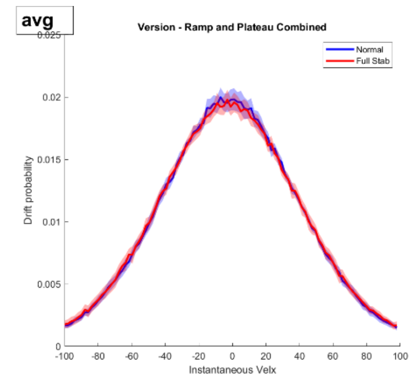
Oculomotor behavior

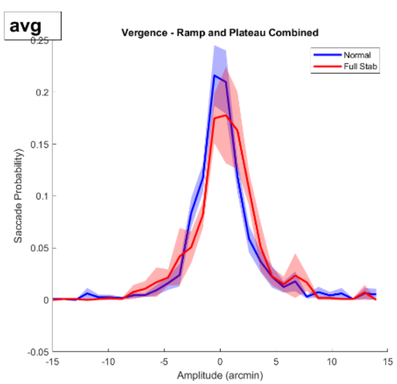
- Eye movements were not different between conditions

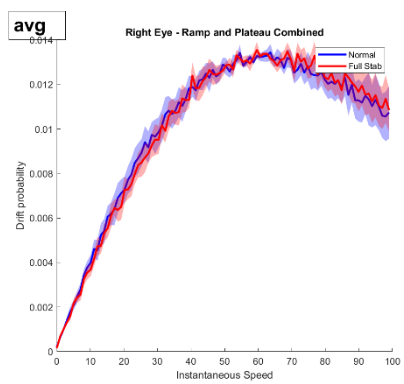
Microsaccade Amplitudes | Drift Speed | Drift horizontal velocity

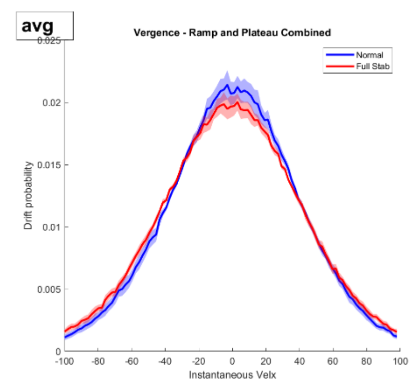












Temporal Transients

		Manipulations	
		Normal	**Full Stab**
Luminance	Signals impinging on retinal photoreceptors	✓	✗
Absolute Disparity	Distance between object on retina and center of fovea	✓	✗
Relative Disparity (1)	Difference of absolute disparities of two objects under the same manipulation	✗	✗
Relative Disparity (2)	One manipulated object, one "normal"	✗	✓

✓ = **changes** in time

✗ = **constant** in time

Viewing Conditions

1. Normal Viewing
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   - Image stabilized independently in each eye
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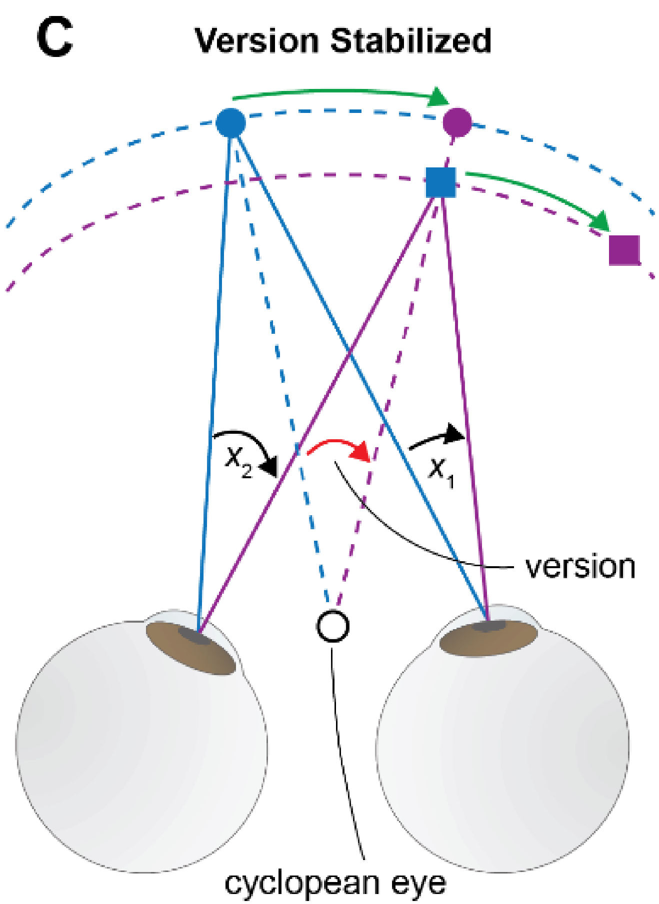
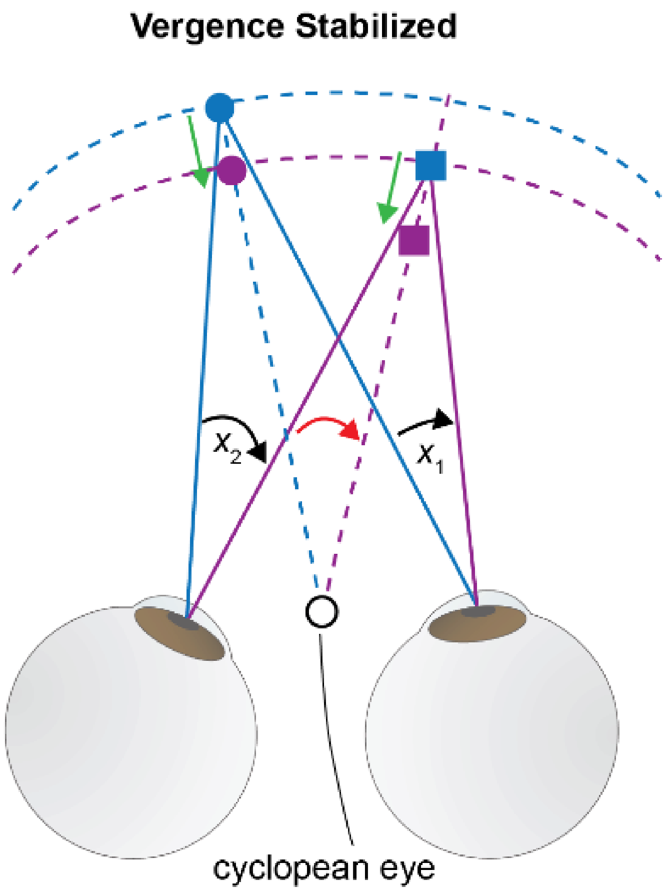
Version Stabilization

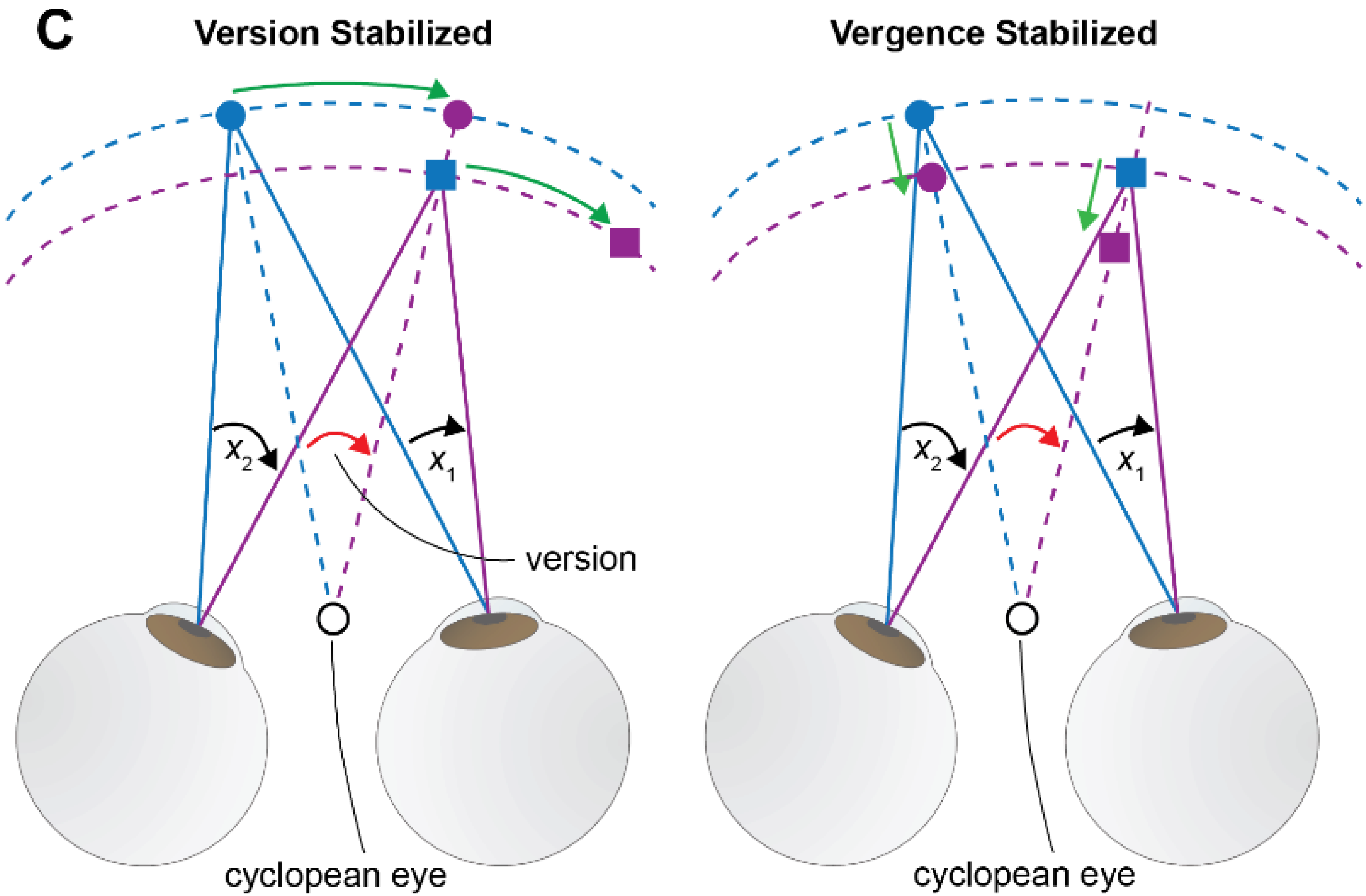


- Retinal consequences of version eye movements are eliminated
- Vergence eye movements still have effect.
- Stimuli are stabilized to the cyclopean eye.
- Stimuli are translated along the isoline of equal vergence.

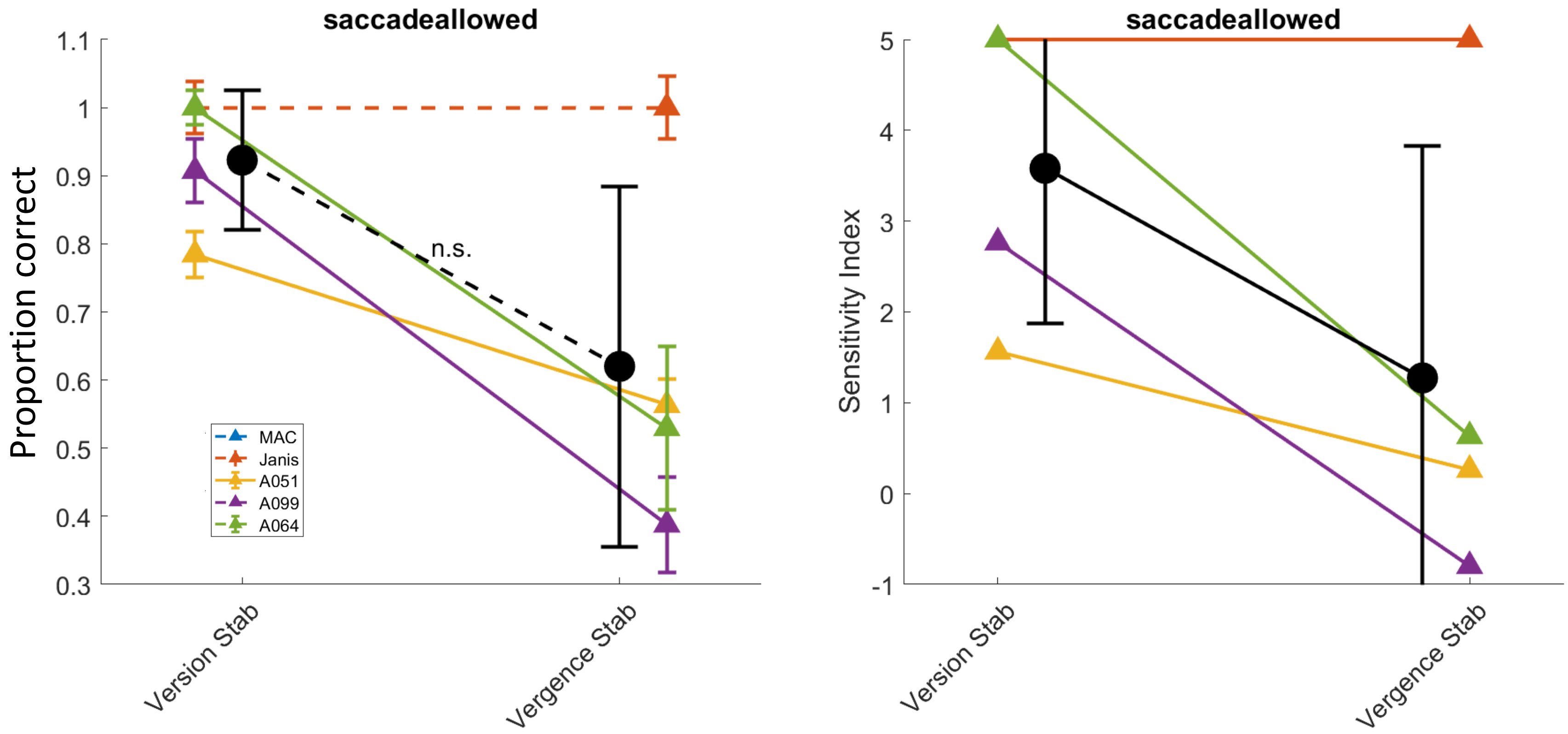
Vergence Stabilization



- Retinal consequences of vergence eye movements are eliminated
- Version eye movements still have effect.
- Stimuli are shifted to stay on the cyclopean line of sight.
- The absolute disparities of the objects are maintained.


C
Version Stabilized
Vergence Stabilized
x_2
x_1
version
cyclopean eye
x_2
x_1
cyclopean eye

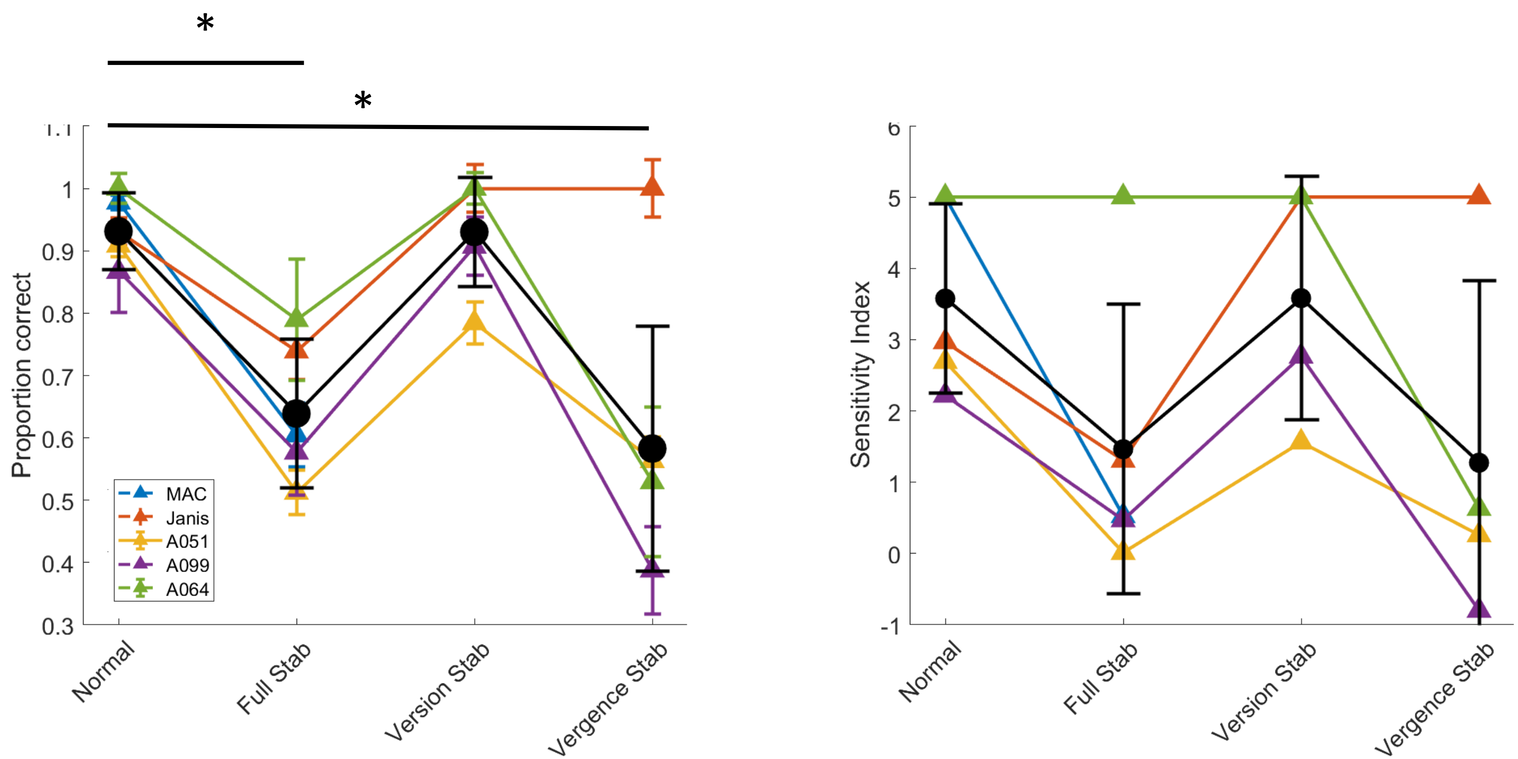
Discrimination Performance



Note that sensitivity index is infinity for some subjects, plotted here with a value of 5.

Discrimination Performance

ANOVA, post-hoc Tukey-Kramer pairwise comparisons



Note that sensitivity index is infinity for some subjects, plotted here with a value of 5.

Temporal Transients

		Manipulations			
		Normal	**Full Stab**	**Vers Stab**	**Verg Stab**
Luminance	Signals impinging on retinal photoreceptors	✓	✗	✓	✓
Absolute Disparity	Distance between object on retina and center of fovea	✓	✗	✓	✗
Relative Disparity (1)	Difference of absolute disparities of two objects under the same manipulation	✗	✗	✗	✗
Relative Disparity (2)	One manipulated object, one "normal"	✗	✓	✓	✓

✓ = **changes** in time

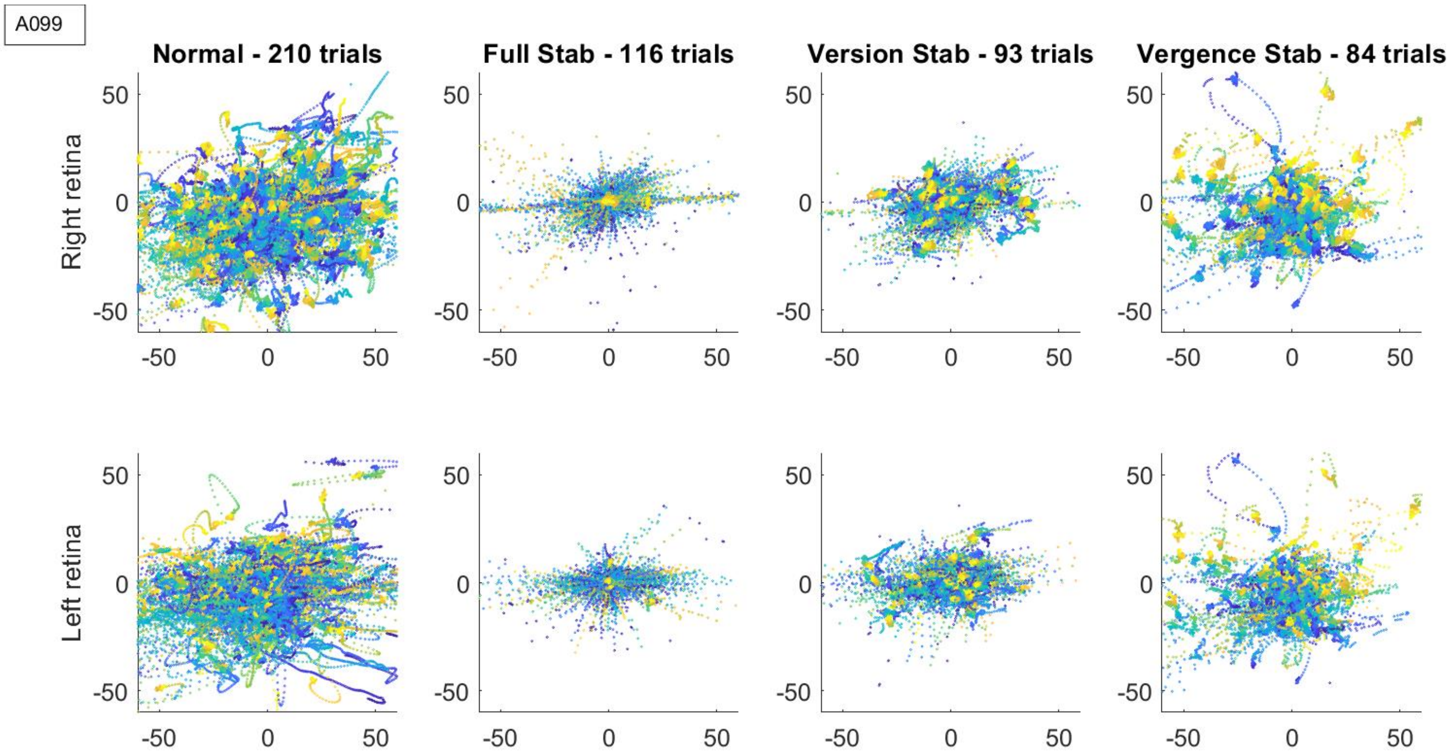
✗ = **constant** in time

Summary & Next Steps

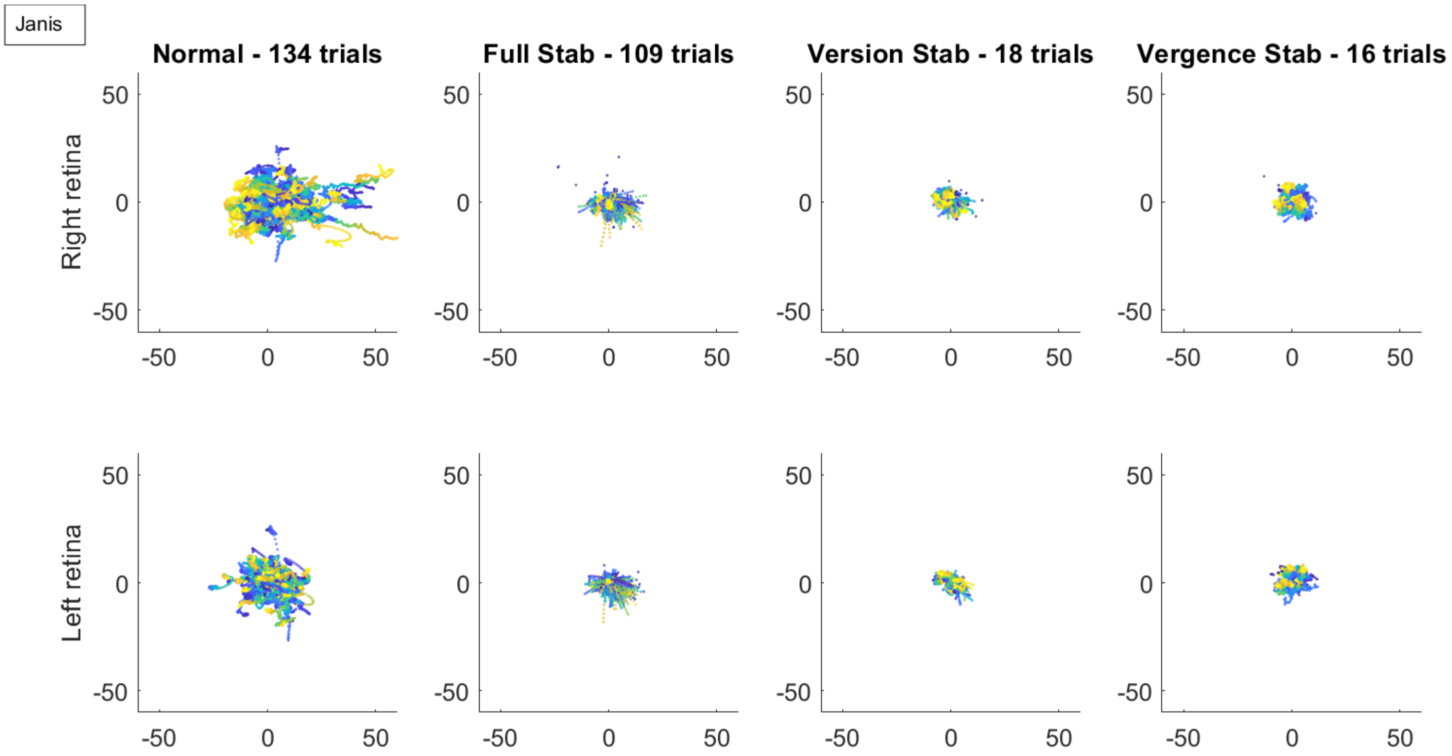
- Discrimination performance is impaired in the absence of retinal image motion
- This decrement in performance is likely due to the loss of absolute disparity modulations

- Analysis of retinal stimulus across conditions: Do version eye movements provide more transients than vergence movements (or vice versa)?

Retinal Motion (Example 1)



Retinal Motion (Example 2)



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