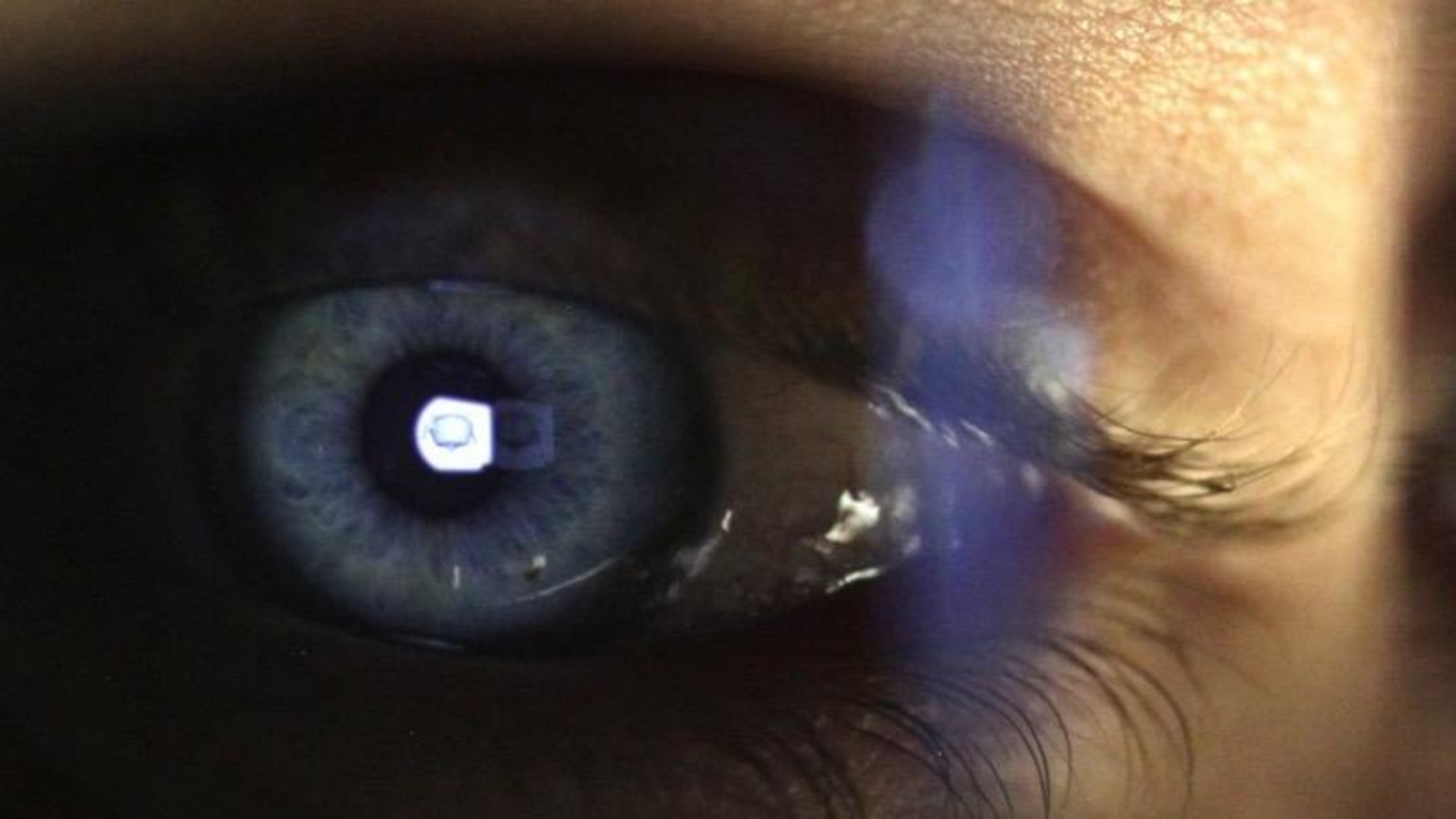
Making Virtual Reality better than Reality?

Gordon Wetzstein
Stanford University

SCI | STANFORD COMPUTATIONAL IMAGING LAB

www.computationalimaging.org



Personal Computer
e.g. Commodore PET 1983

Laptop
e.g. Apple MacBook

Smartphone
e.g. Google Pixel

AR/VR
e.g. Microsoft Hololens

???

A Brief History of Virtual Reality

Stereoscopes
Wheatstone, Brewster, …

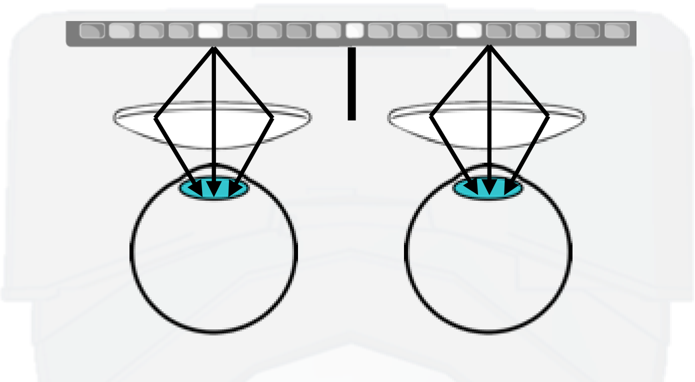
VR & AR
Ivan Sutherland

Nintendo Virtual Boy

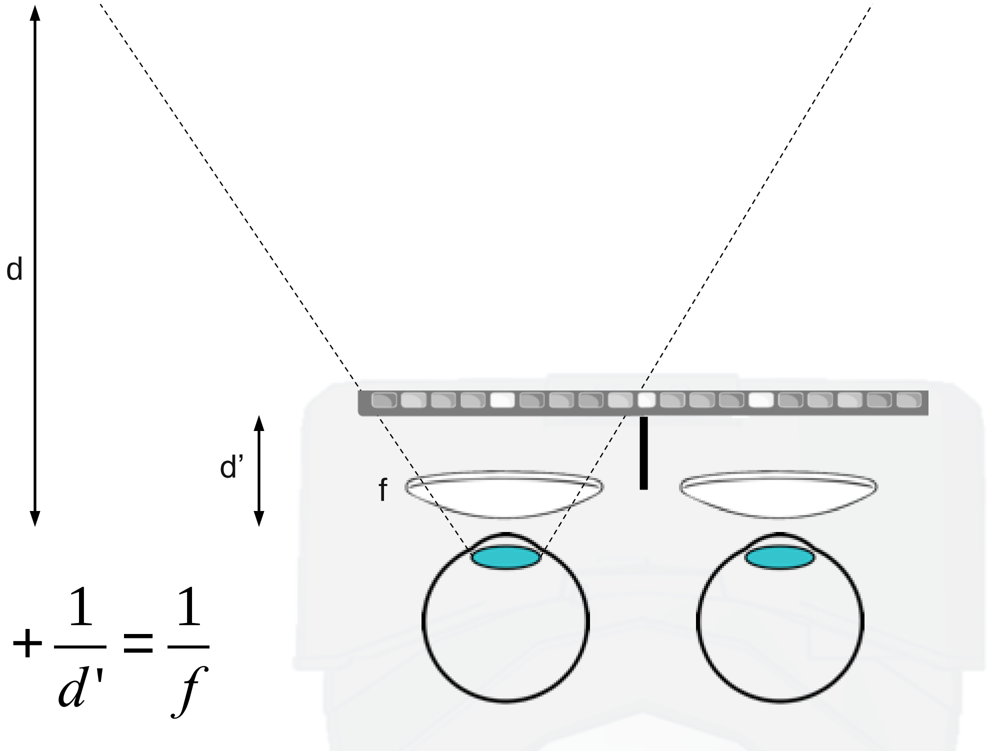
VR explosion
Oculus, Sony, HTC, MS, …

Where we are now

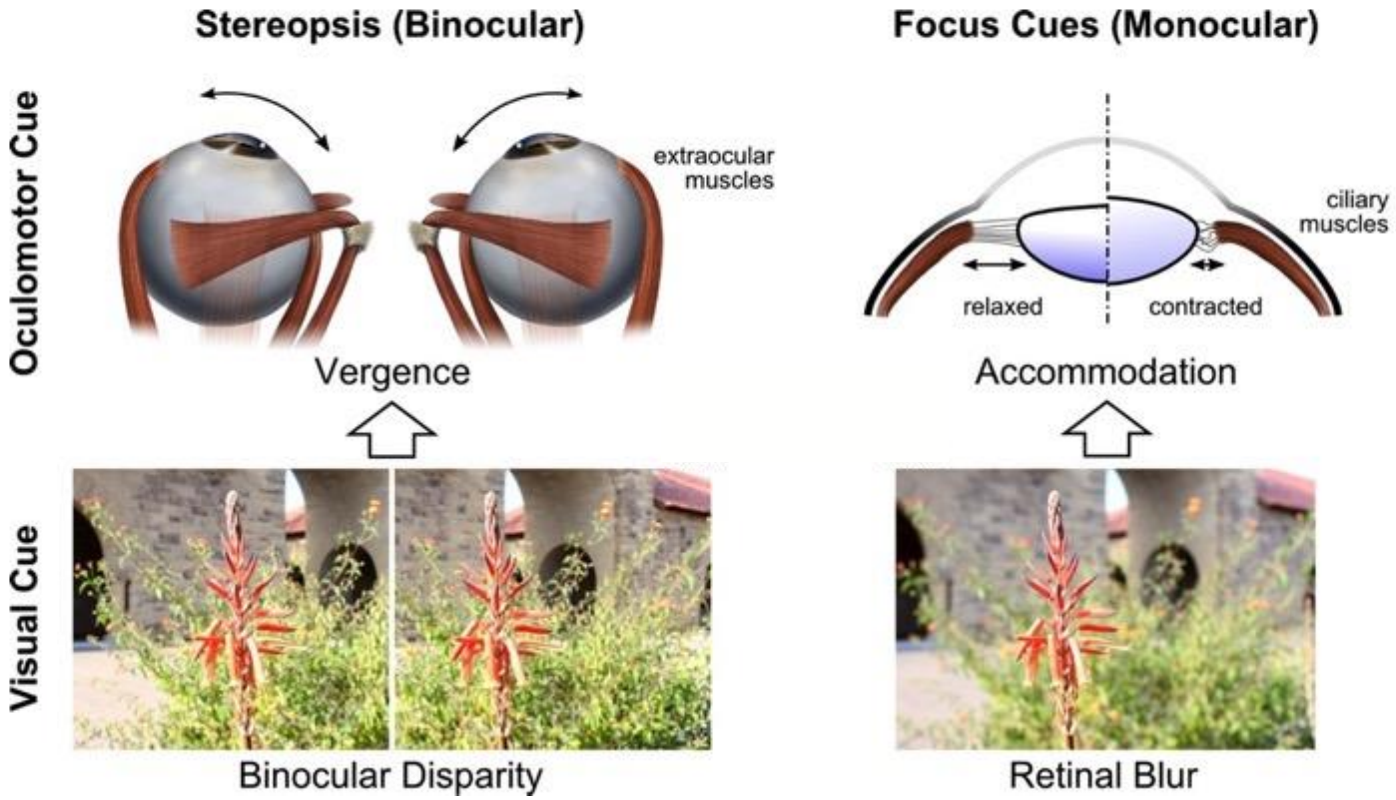
IFIXIT teardown

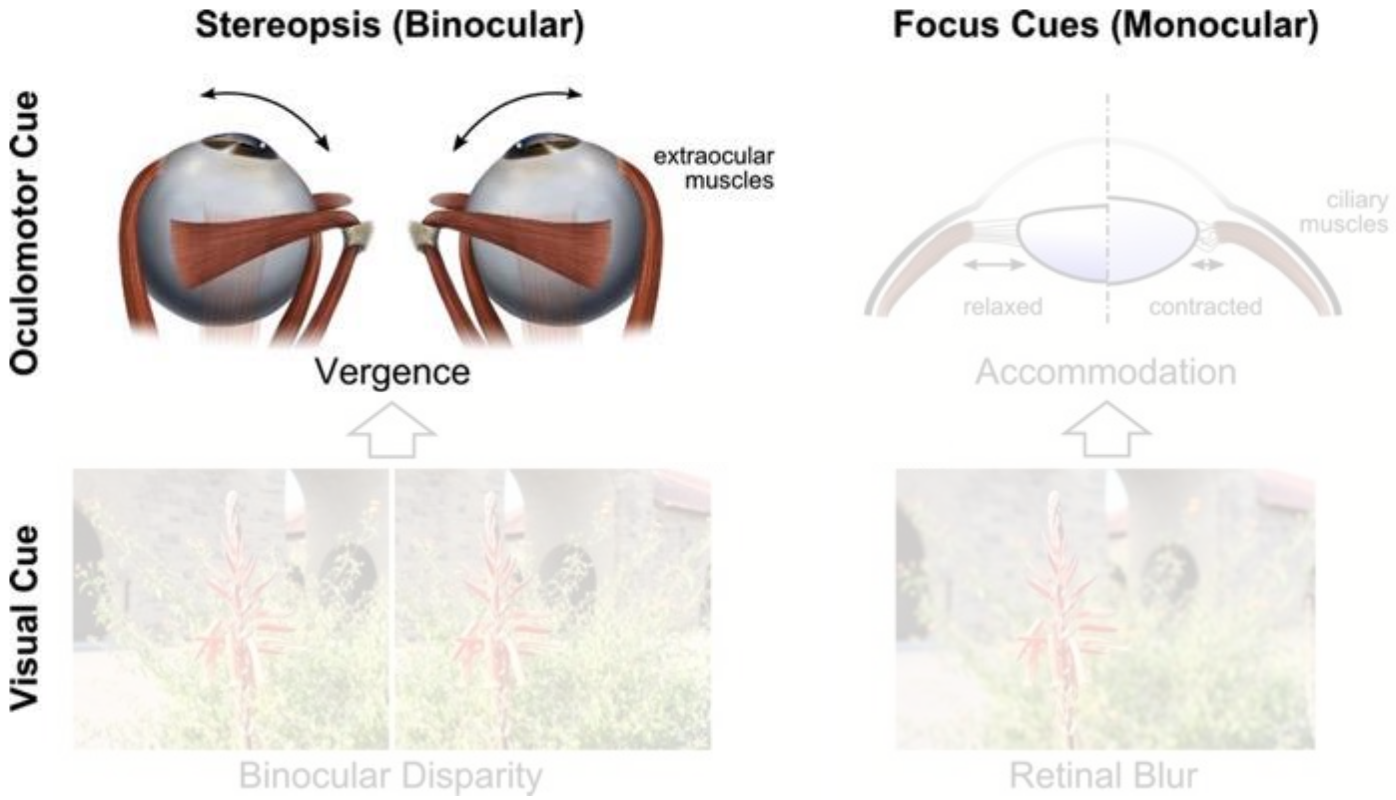


Magnified Display



$$\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}$$


Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
ciliary muscles
relaxed
contracted
Vergence
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur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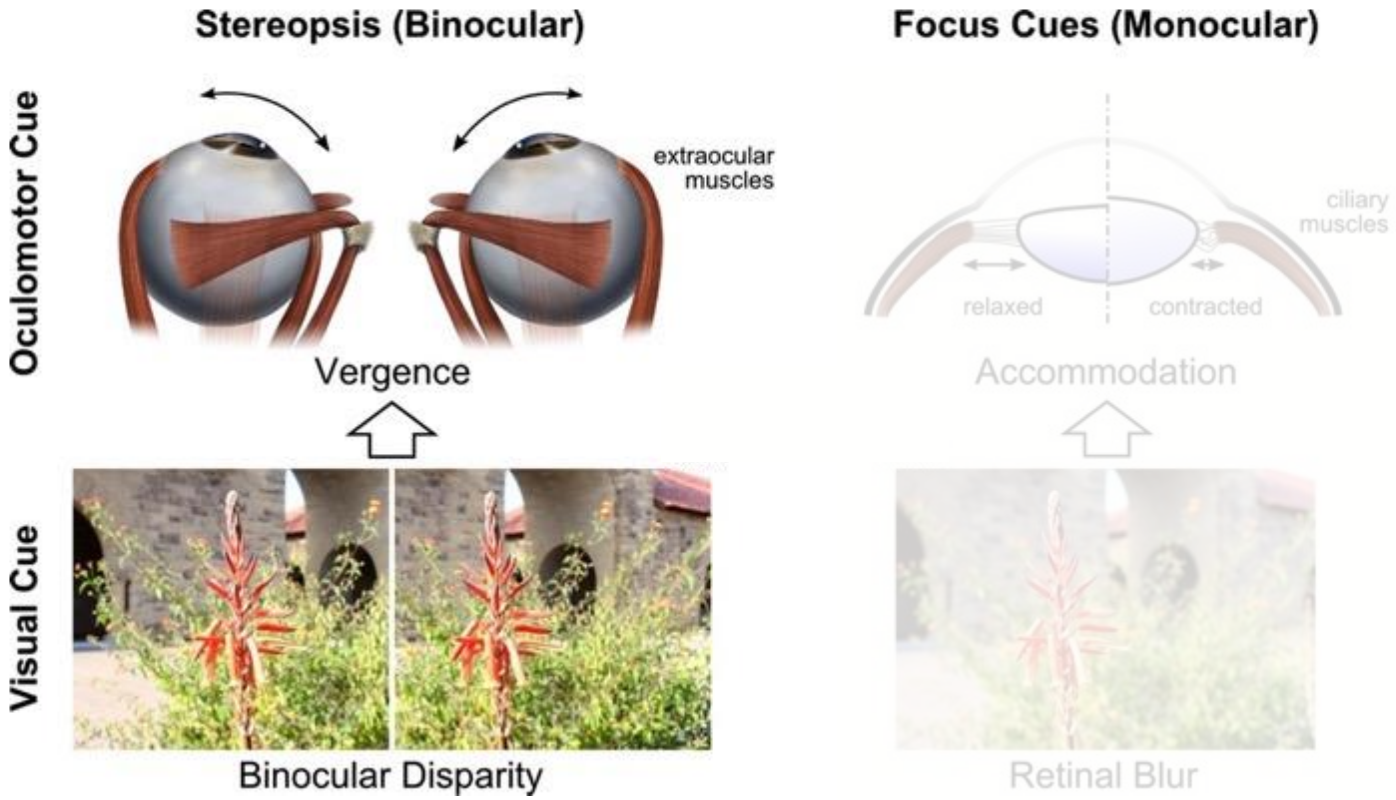

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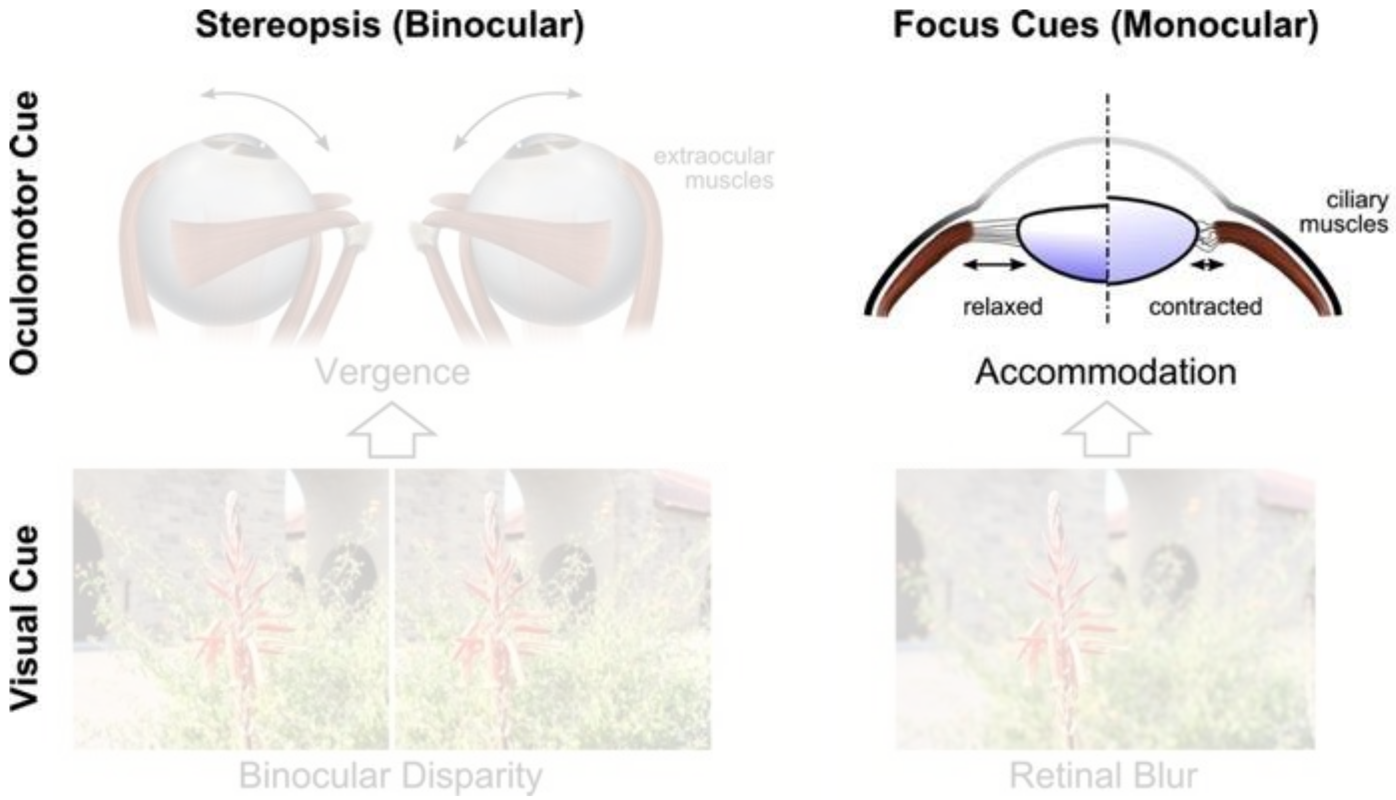

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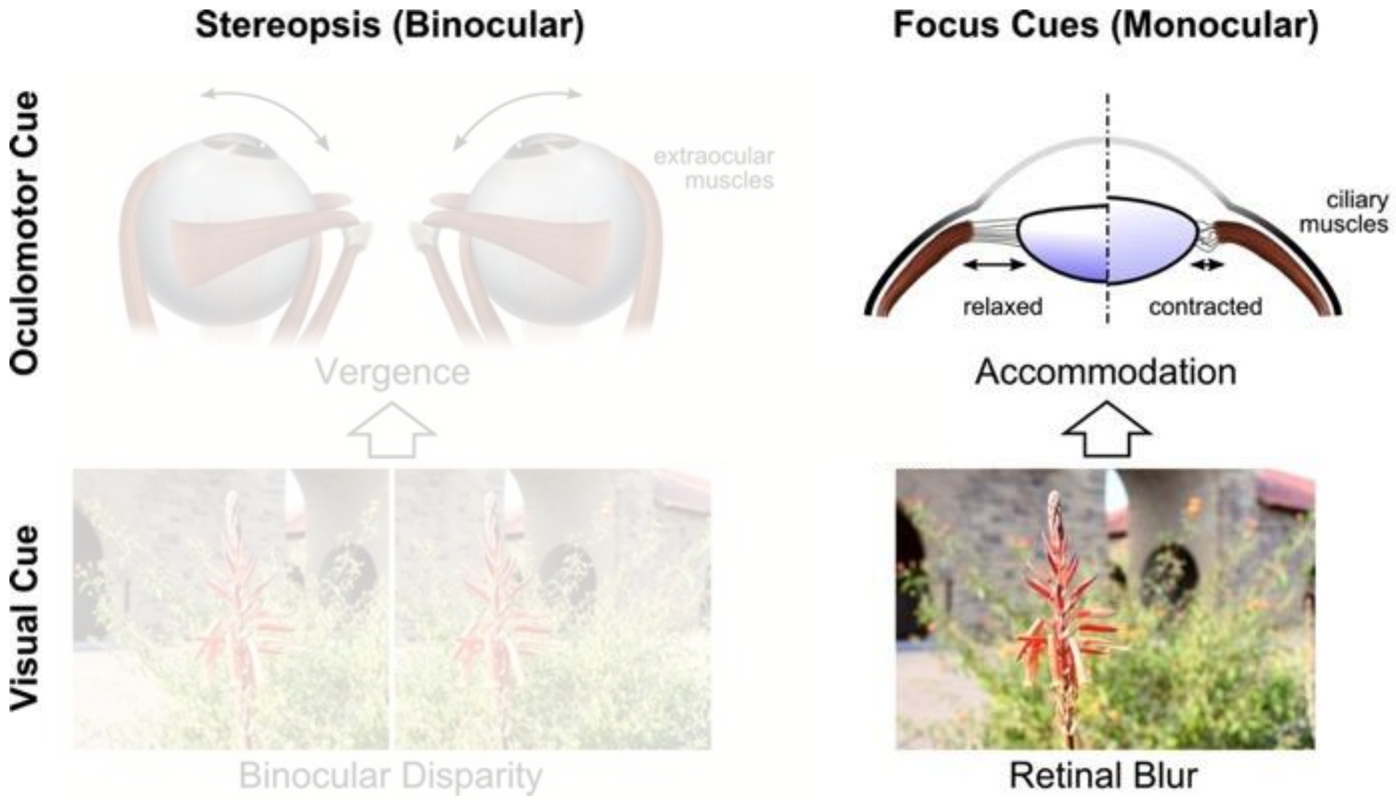
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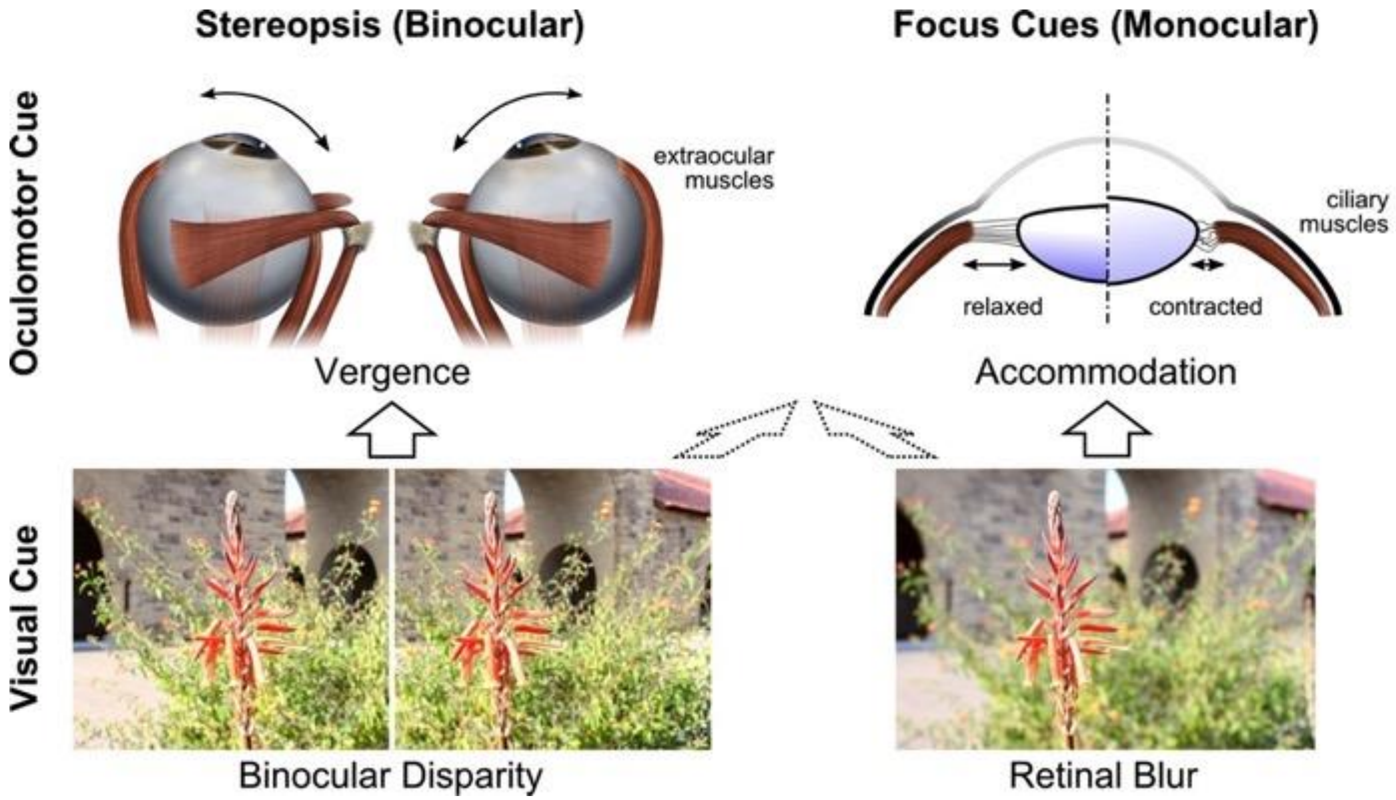
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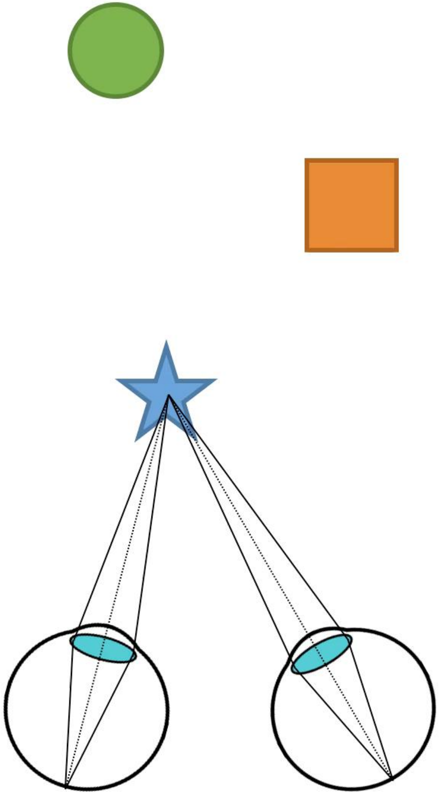
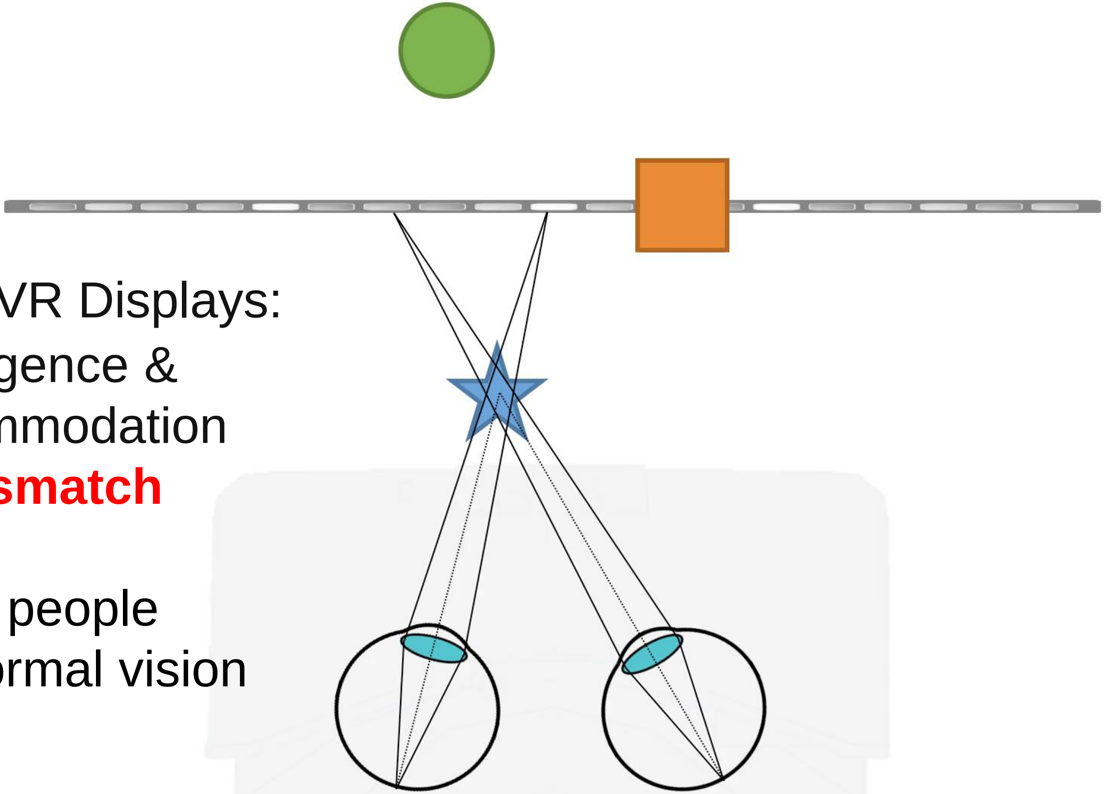
Real World:
Vergence &
Accommodation
Match!

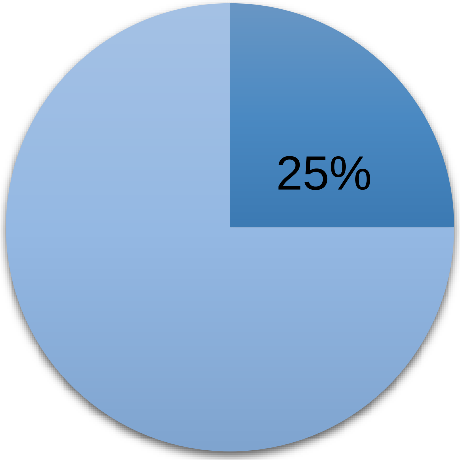


Current VR Displays:
Vergence &
Accommodation
Mismatch

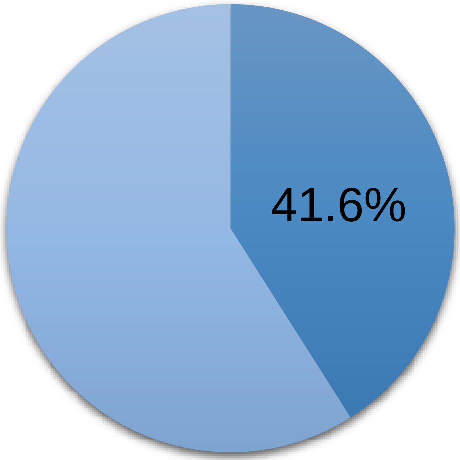
for people
with normal vision



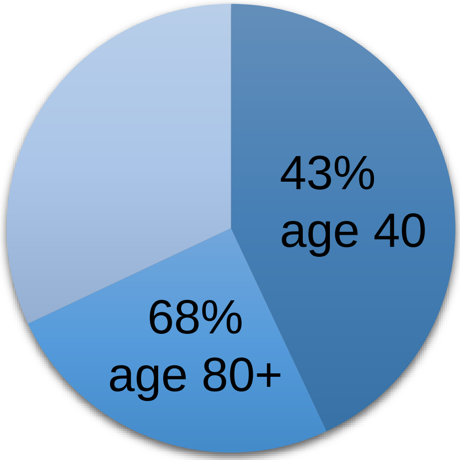
How Many People Have Normal Vision?



Hyperopia
[Krachmer et al. 2005]



Myopia
[Vitale et al. 2009]

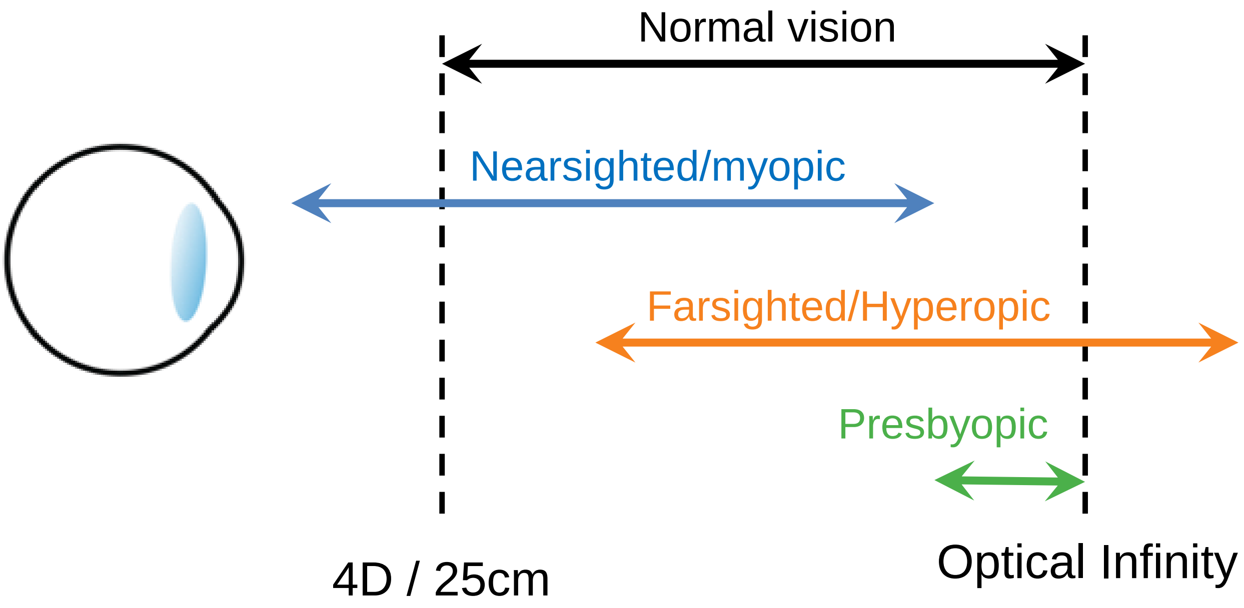


Presbyopia
[Katz et al. 1997]

all numbers of US population

Nearsightedness & Farsightedness

Focal range (range of clear vision)



Modified from Pamplona et al, Proc. of SIGGRAPH 2010

Computational Near-eye Displays

- Q1: Can computational displays effectively replace glasses in VR/AR?

- Q2: How to address the vergence-accommodation conflict for users of different ages?

- Q3: What are (in)effective near-eye display technologies?

possible solutions: gaze-contingent focus, monovision, multiplane, light field displays, …

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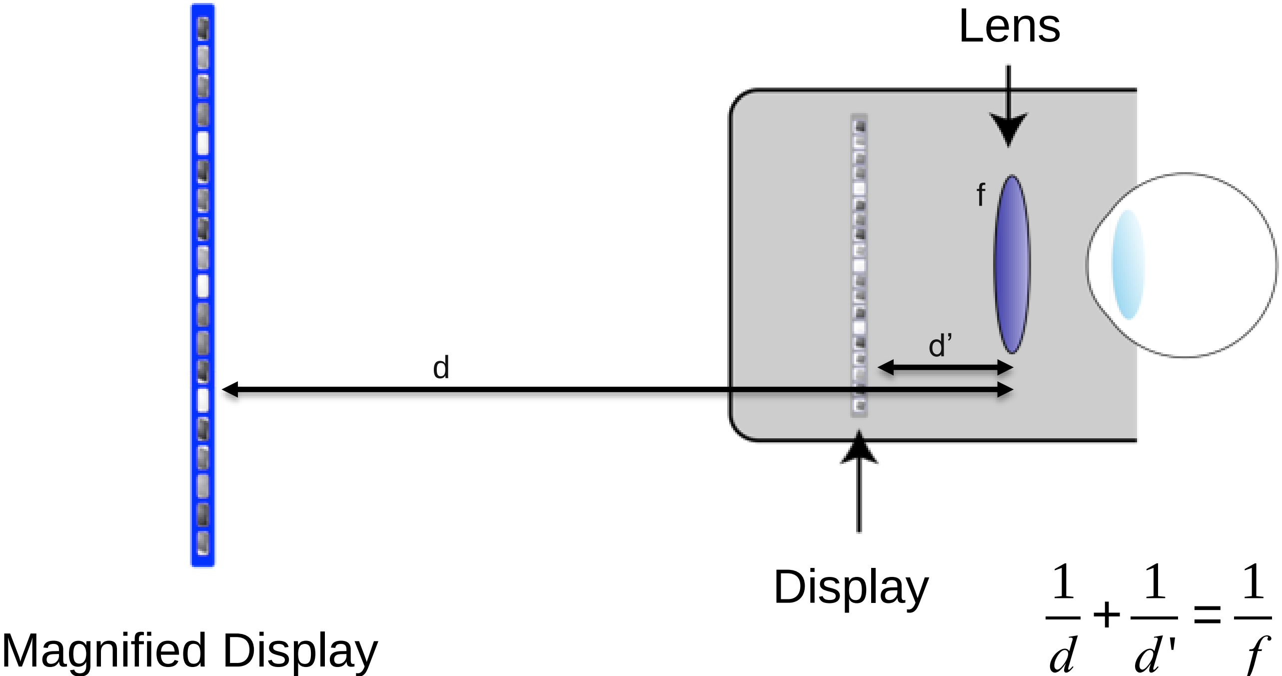
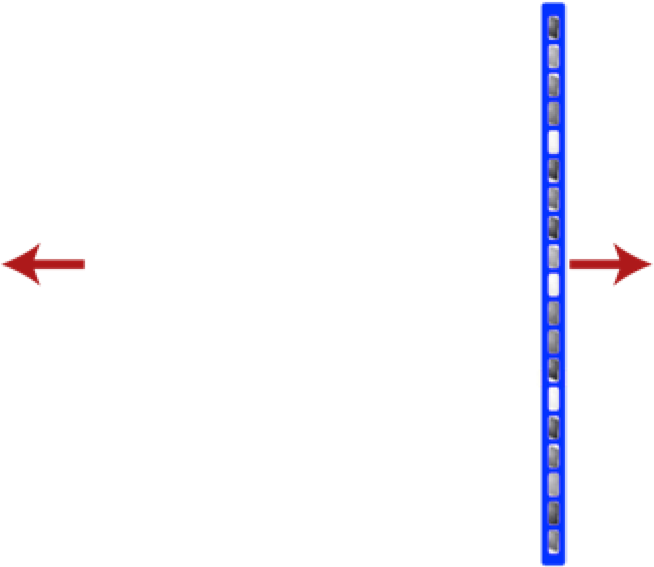
Fixed Focus

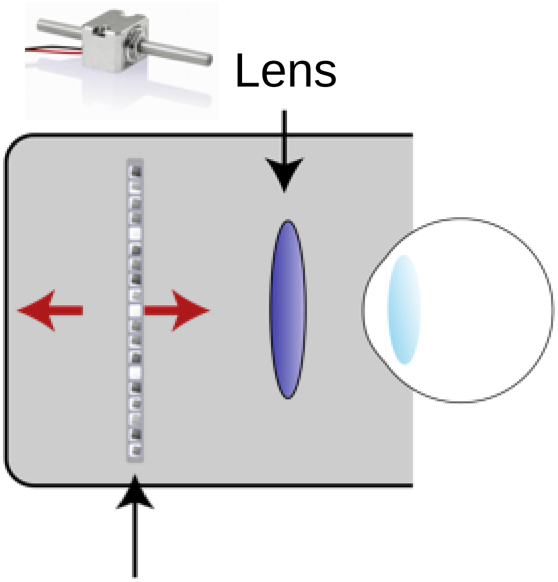


$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{f}$$

Adaptive Focus

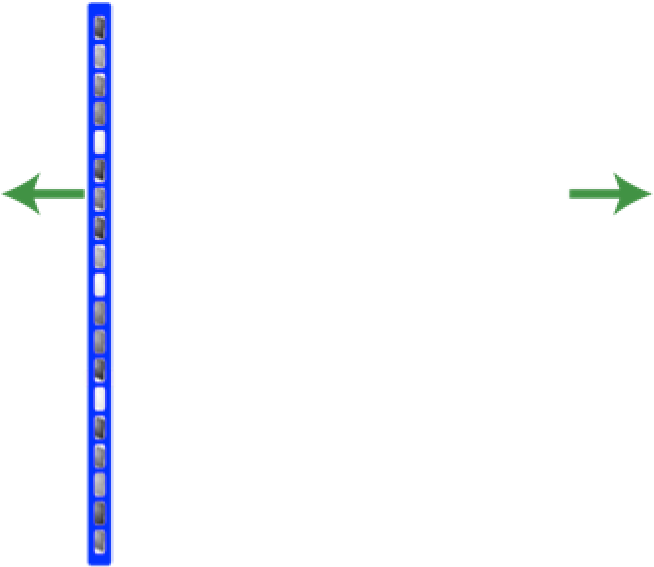


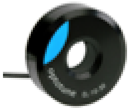
Magnified Display



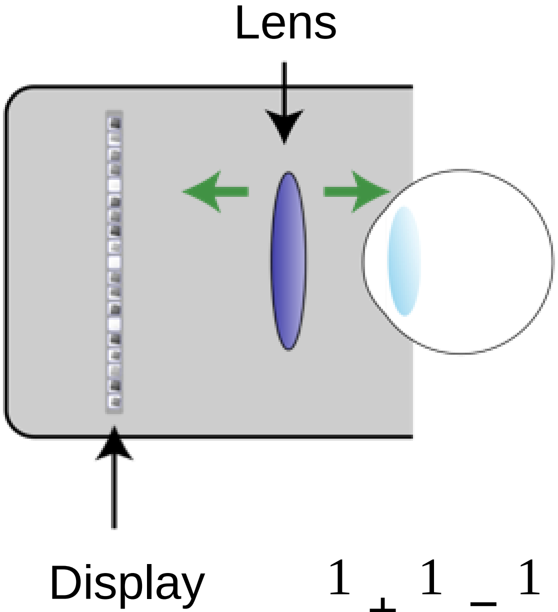
$$\frac{1}{d}+\frac{1}{\boxed{d'}}=\frac{1}{f}$$

Adaptive Focus





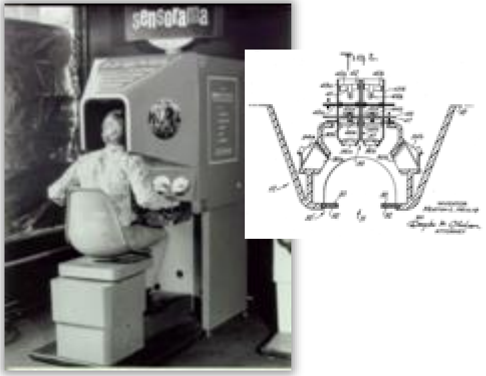
focus-tunable
lens → vary f



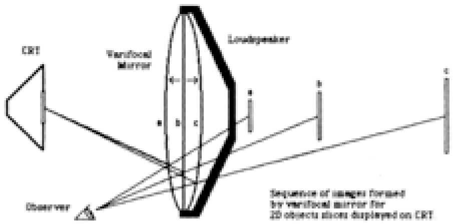
$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{\boxed{f}}$$

Magnified Display

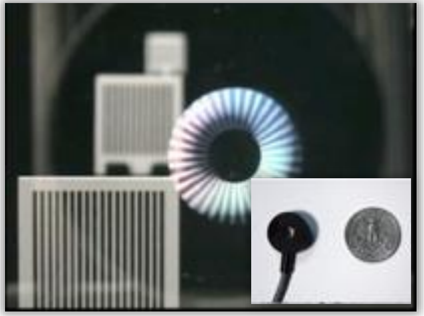
Adaptive Focus - History



manual focus adjustment
Heilig 1962

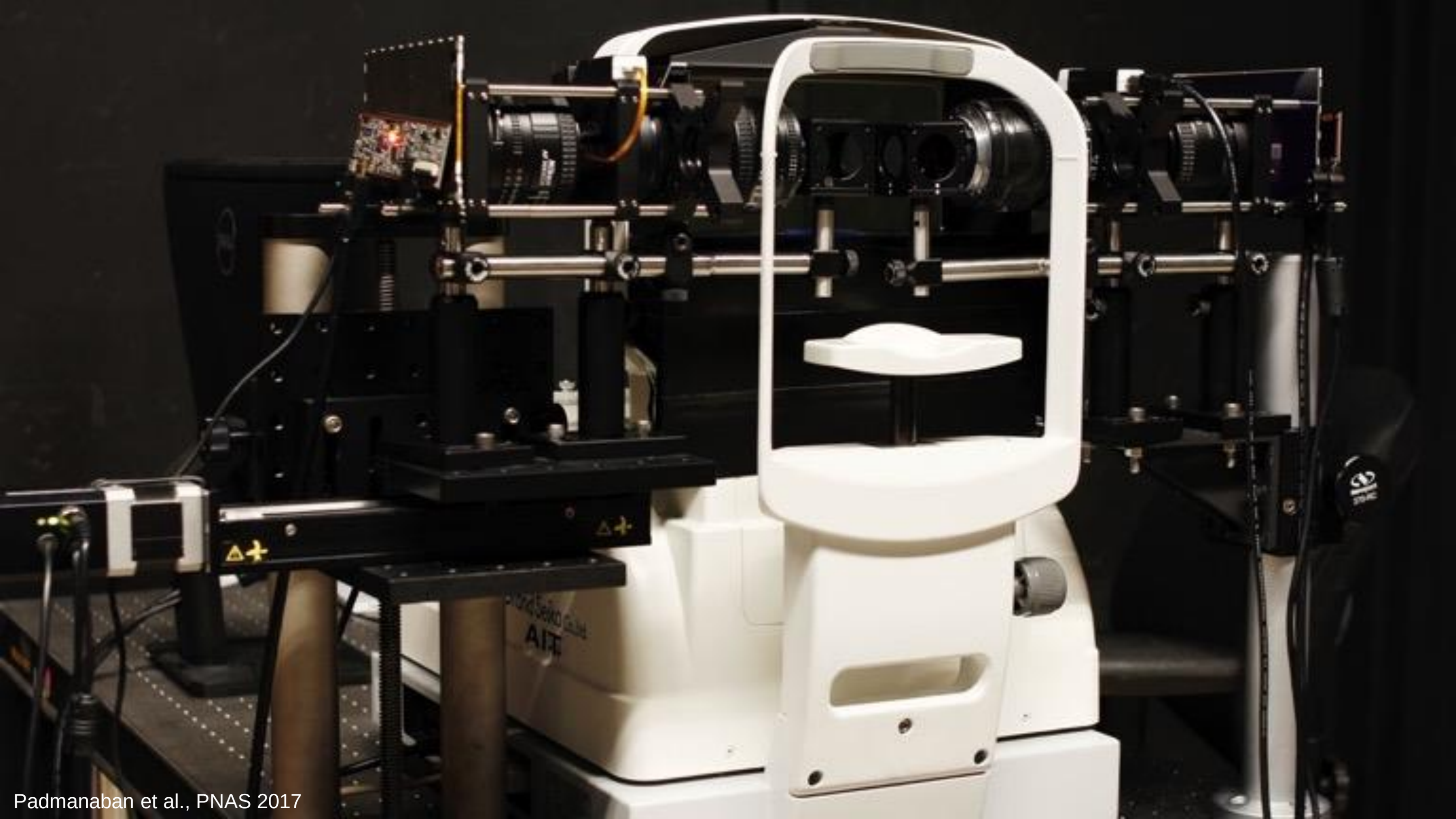


automatic focus adjustment
Mills 1984



deformabe mirrors & lenses
McQuaide 2003, Liu 2008

- M. Heilig “Sensorama”, 1962 (US Patent #3,050,870)
- P. Mills, H. Fuchs, S. Pizer “High-Speed Interaction On A Vibrating-Mirror 3D Display”, SPIE 0507 1984
- S. Shiwa, K. Omura, F. Kishino “Proposal for a 3-D display with accommodative compensation: 3DDAC”, JSID 1996
- S. McQuaide, E. Seibel, J. Kelly, B. Schowengerdt, T. Furness “A retinal scanning display system that produces multiple focal planes with a deformable membrane mirror”, Displays 2003
- S. Liu, D. Cheng, H. Hua “An optical see-through head mounted display with addressable focal planes”, Proc. ISMAR 2008



Padmanaban et al., PNAS 2017

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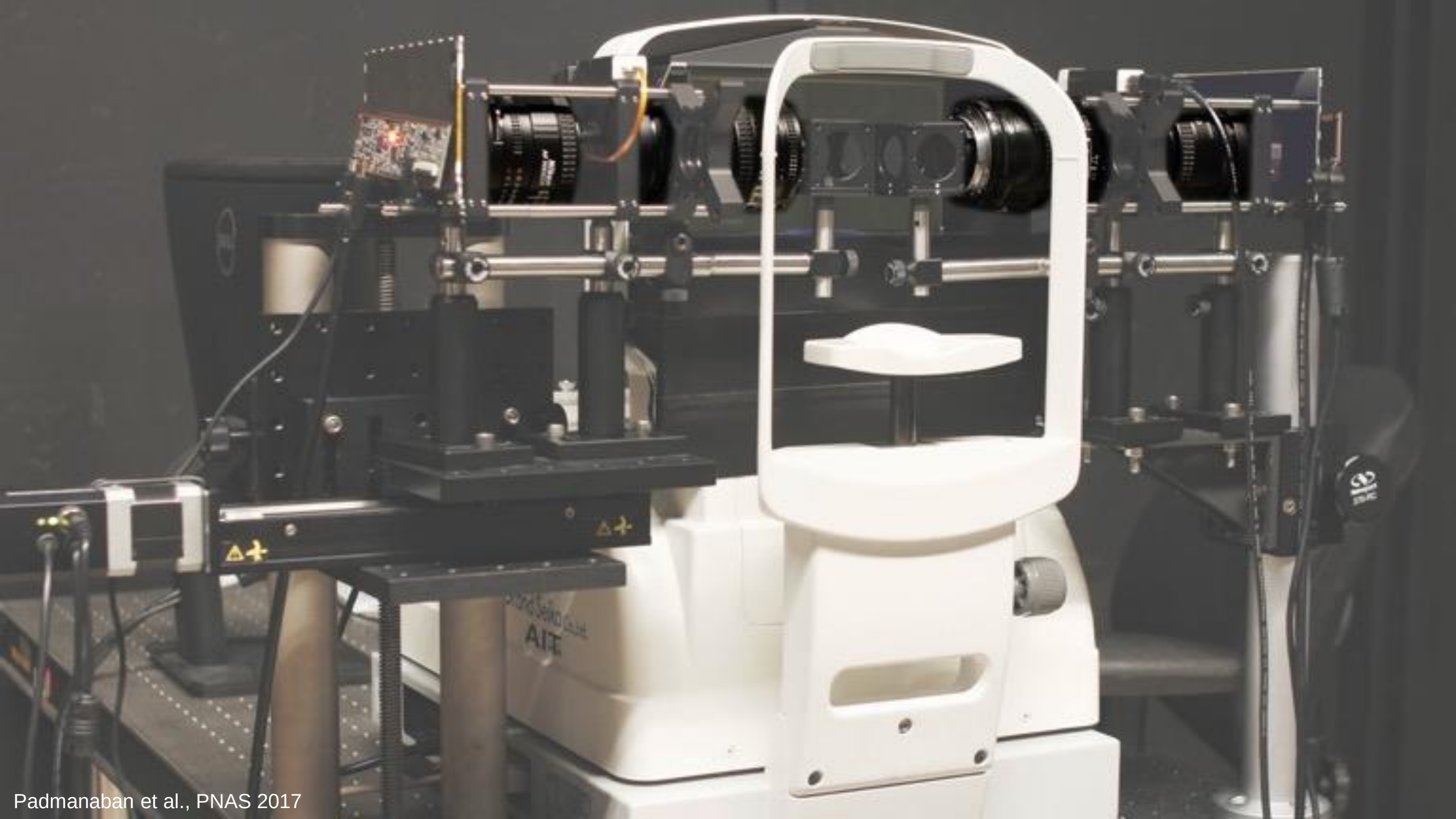

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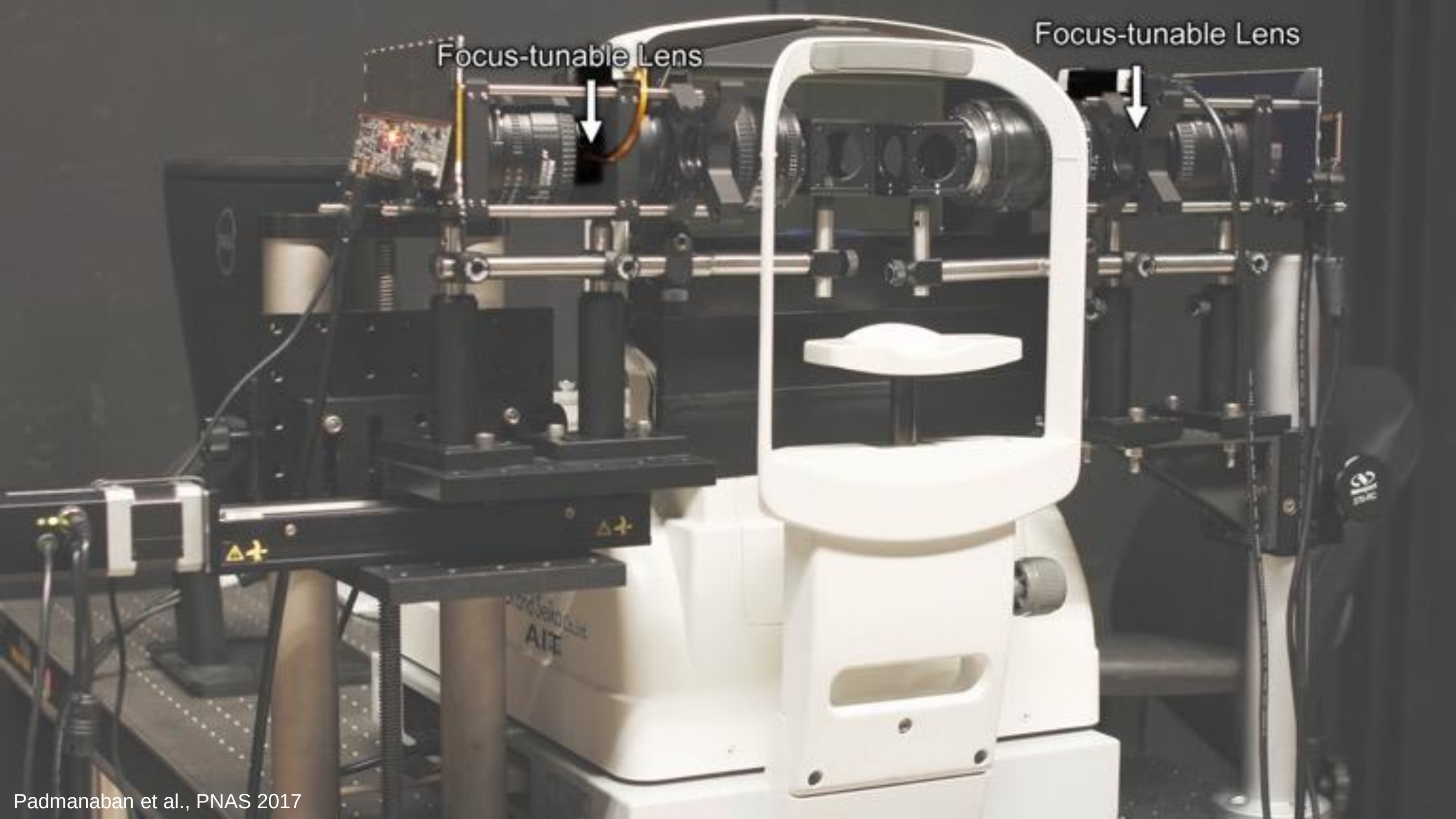

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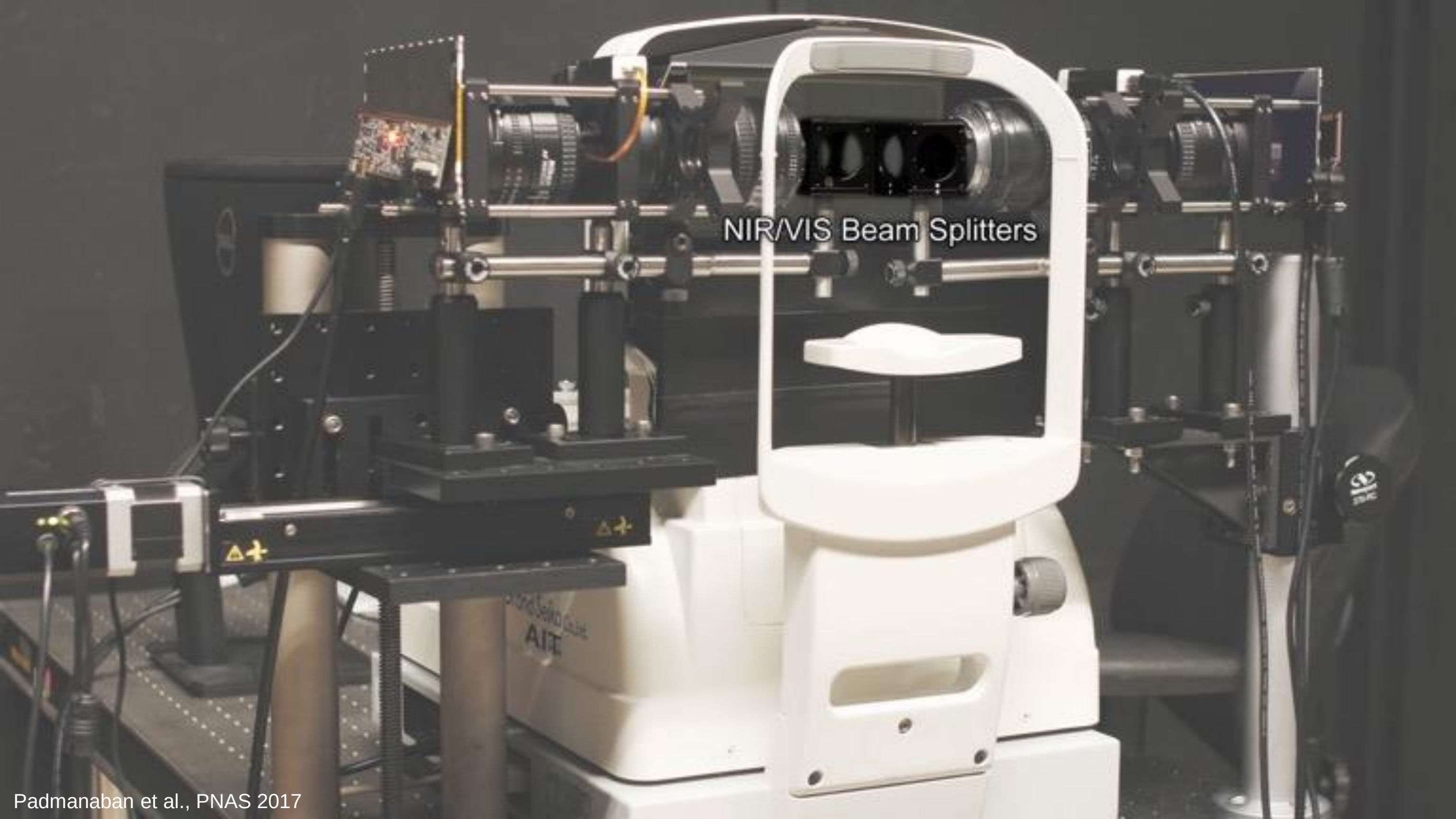

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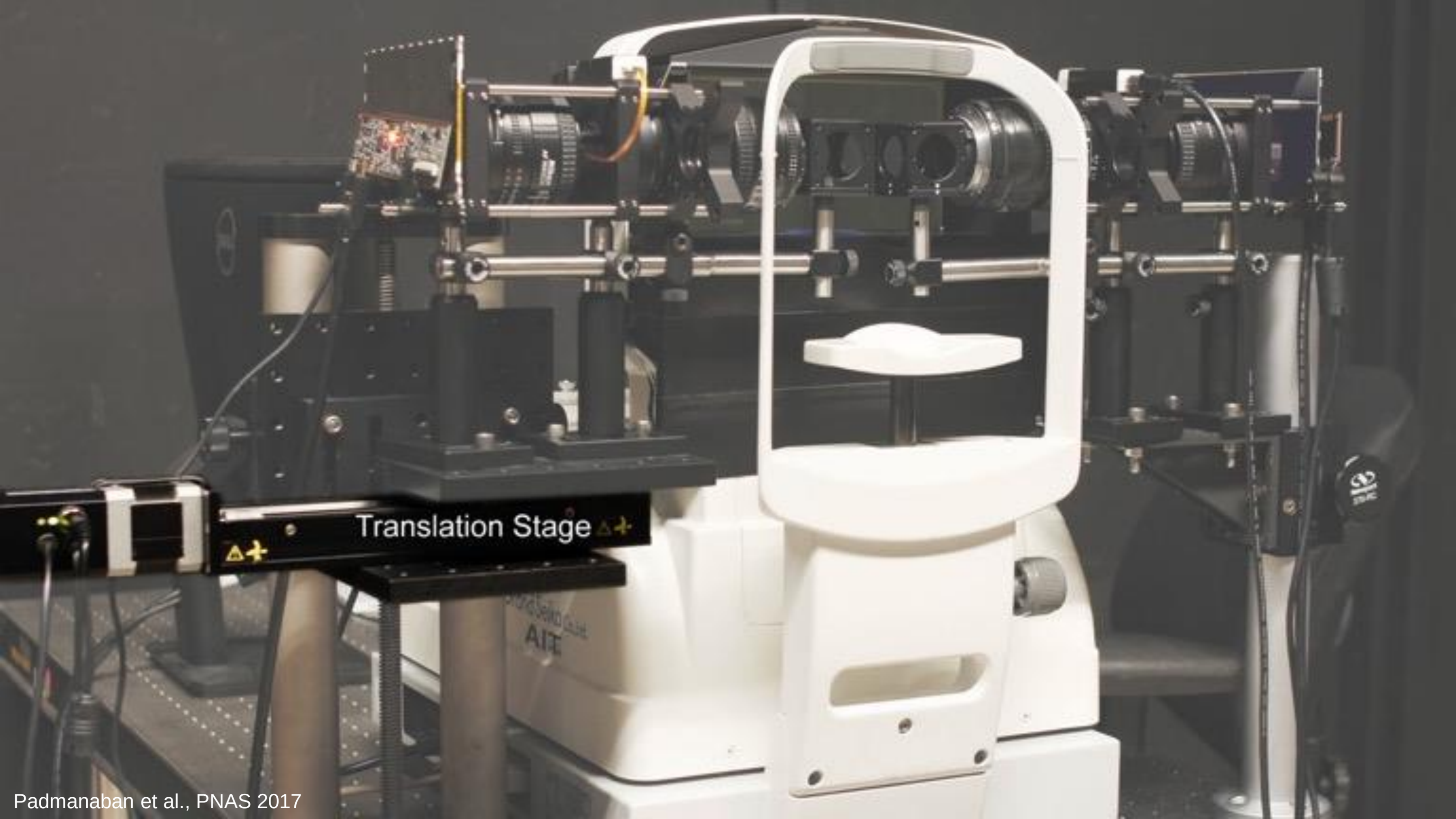

Padmanaban et al., PNAS 2017

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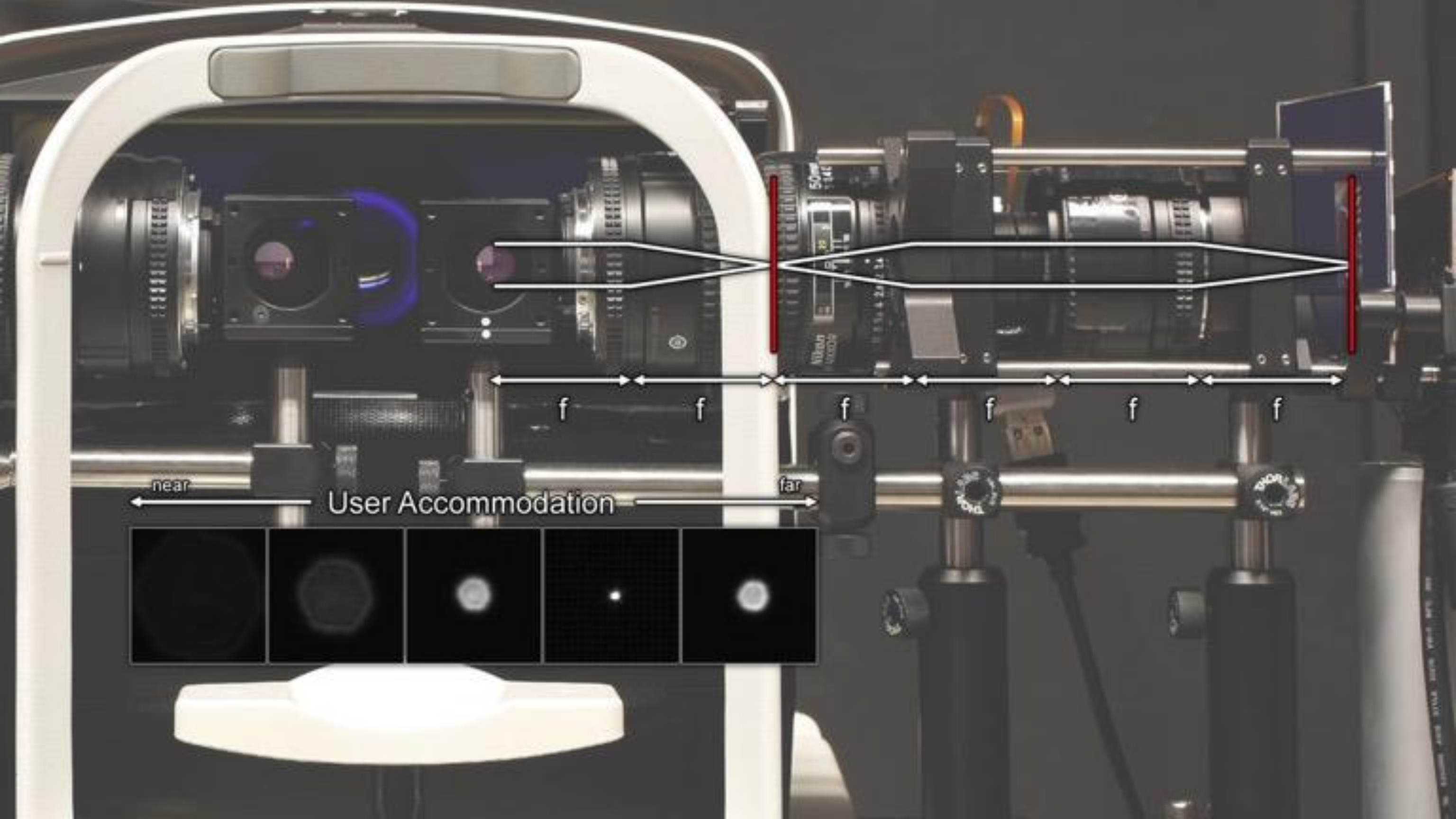
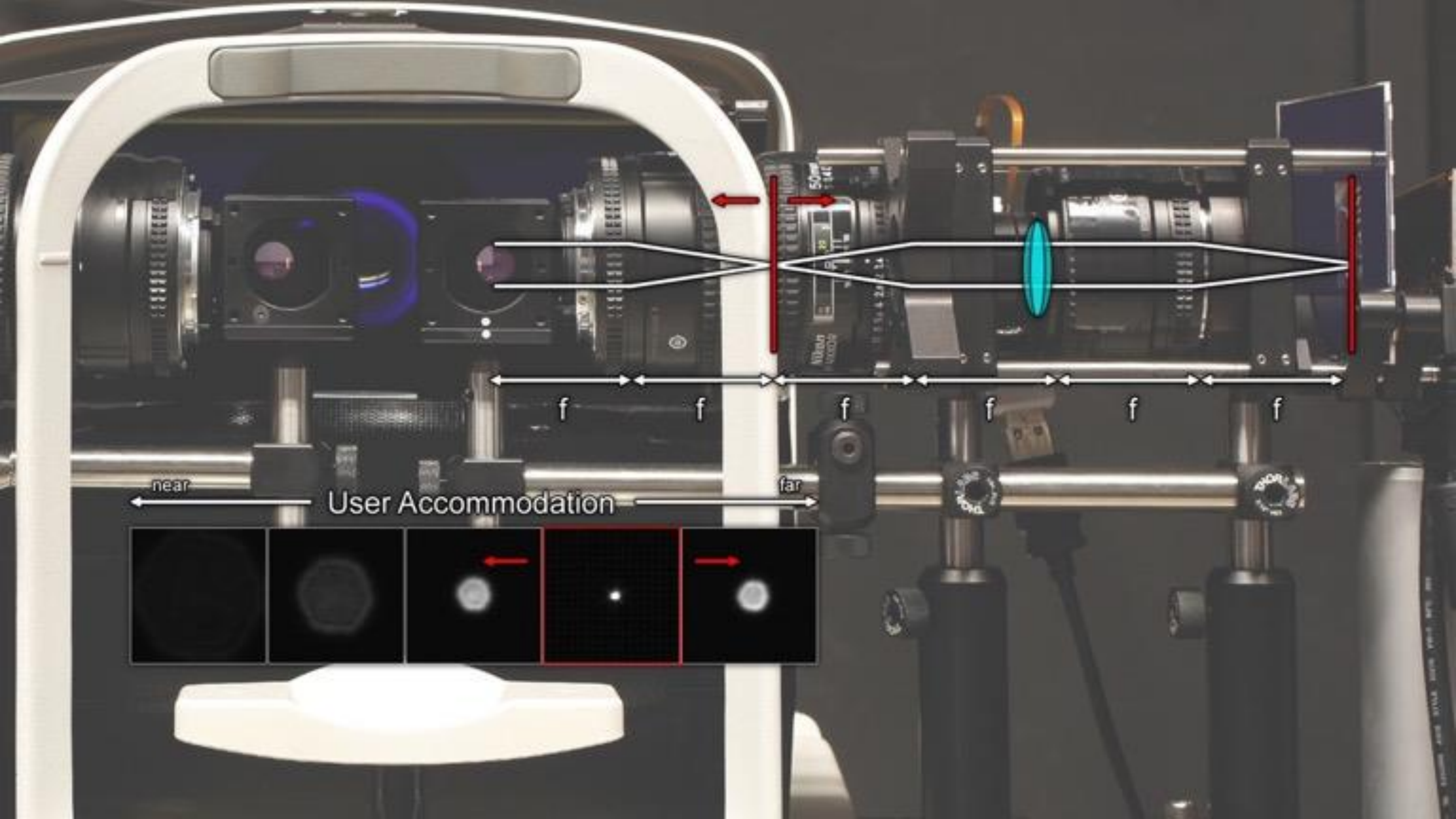

f
f
f
f
f
f
near
User Accommodation
far

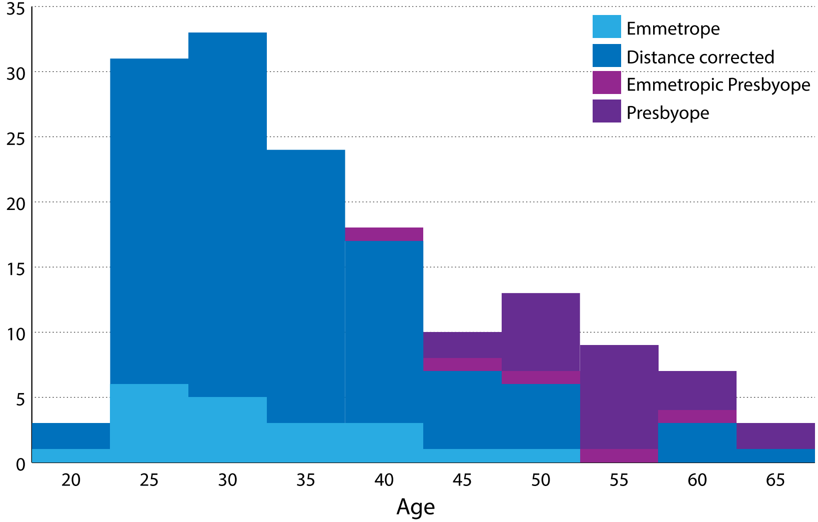

f
f
f
f
f
f
near
User Accommodation
far

EyeNetra.com

at ACM SIGGRAPH 2016

EyeNetra.com

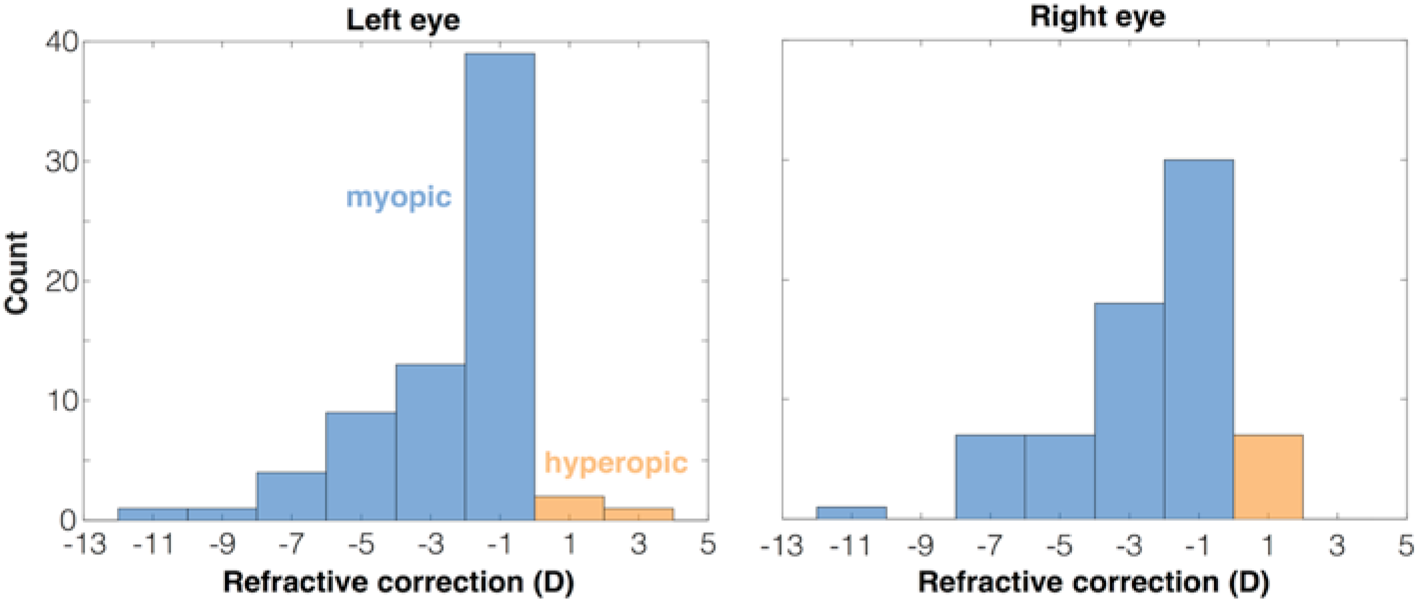
participants of the study, 152 total



at ACM SIGGRAPH 2016

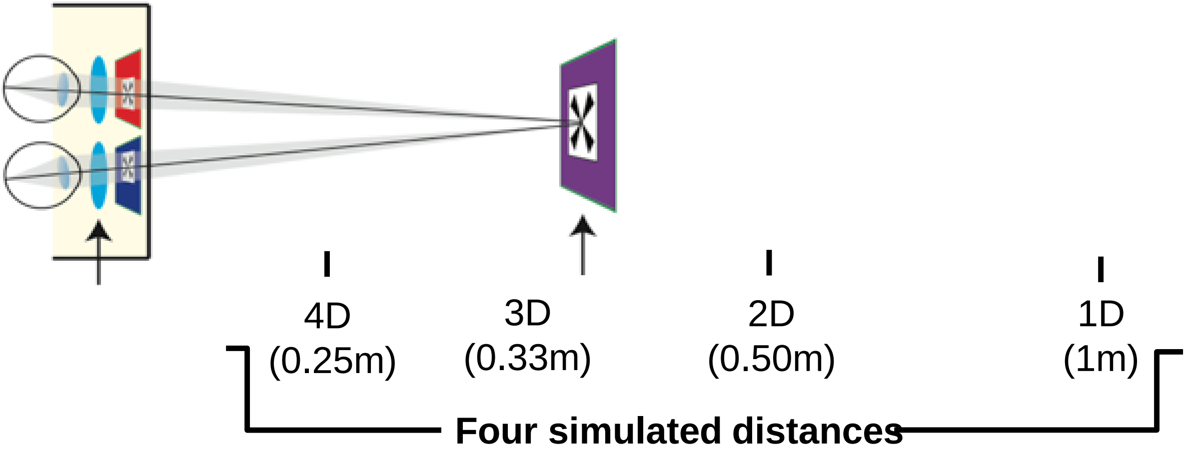
Participants - Prescription

n = 70, ages 21-64



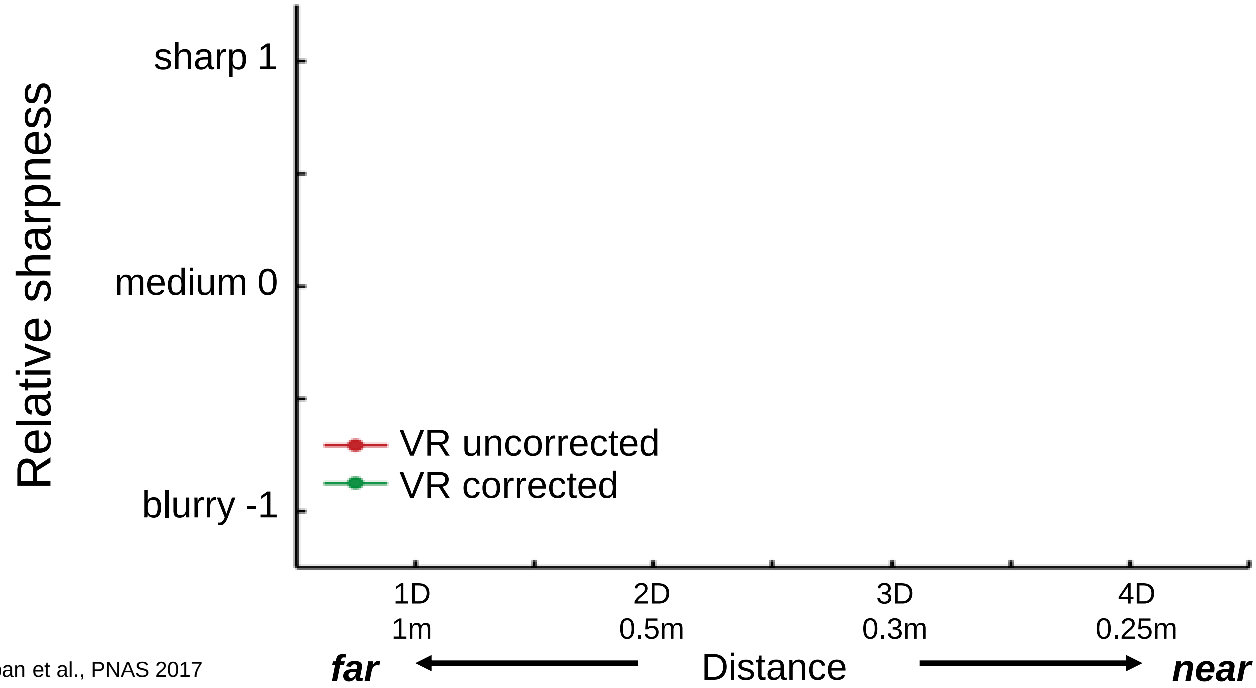
Padmanaban et al., PNAS 2017

Task



How sharp is the target? (blurry, medium, sharp)
Is the target fused? (yes, no)

Results - Sharpness



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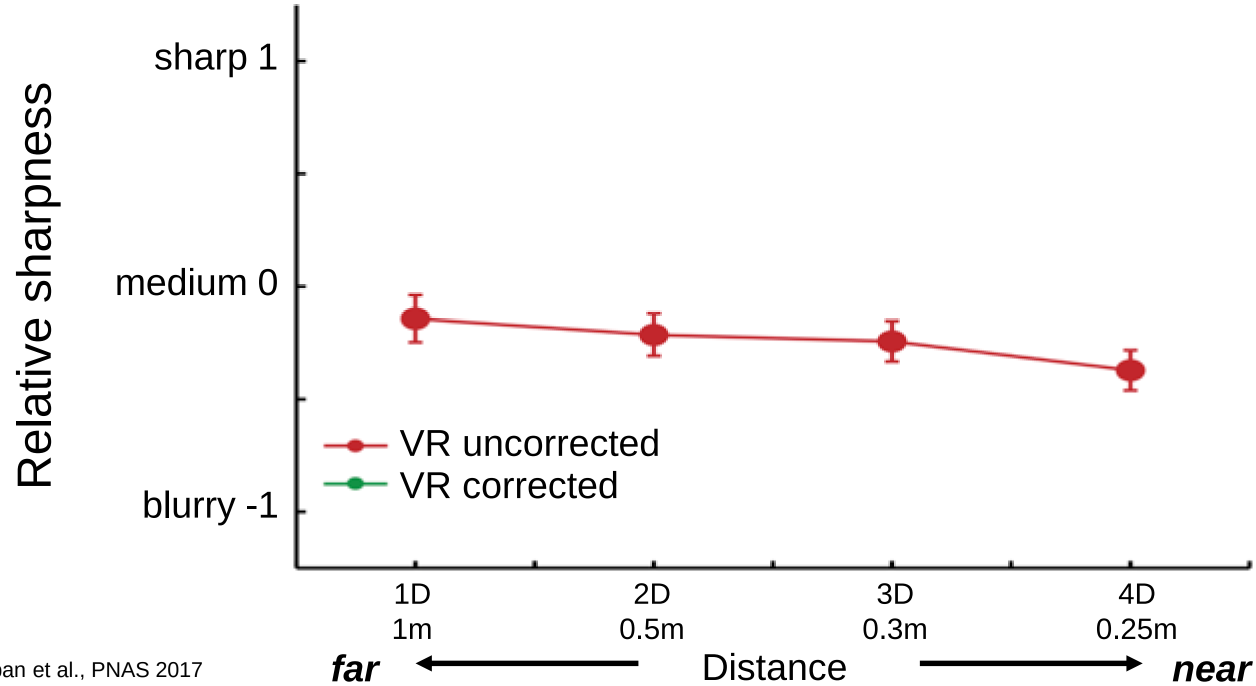

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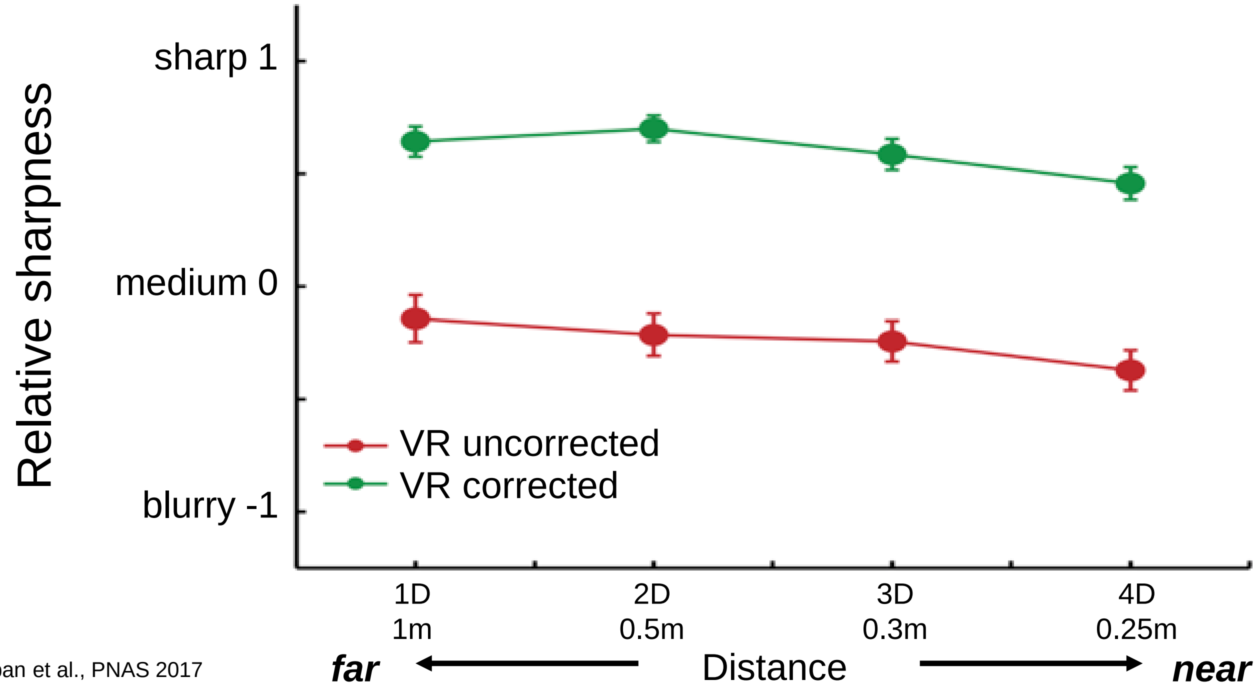

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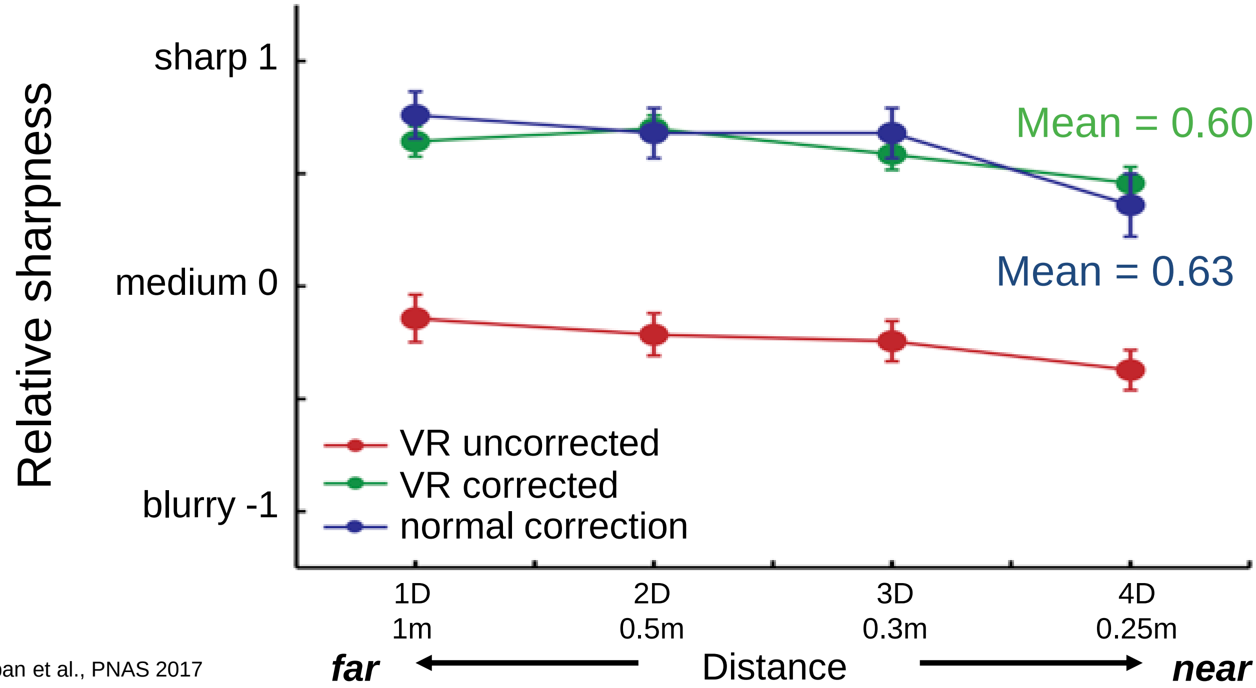
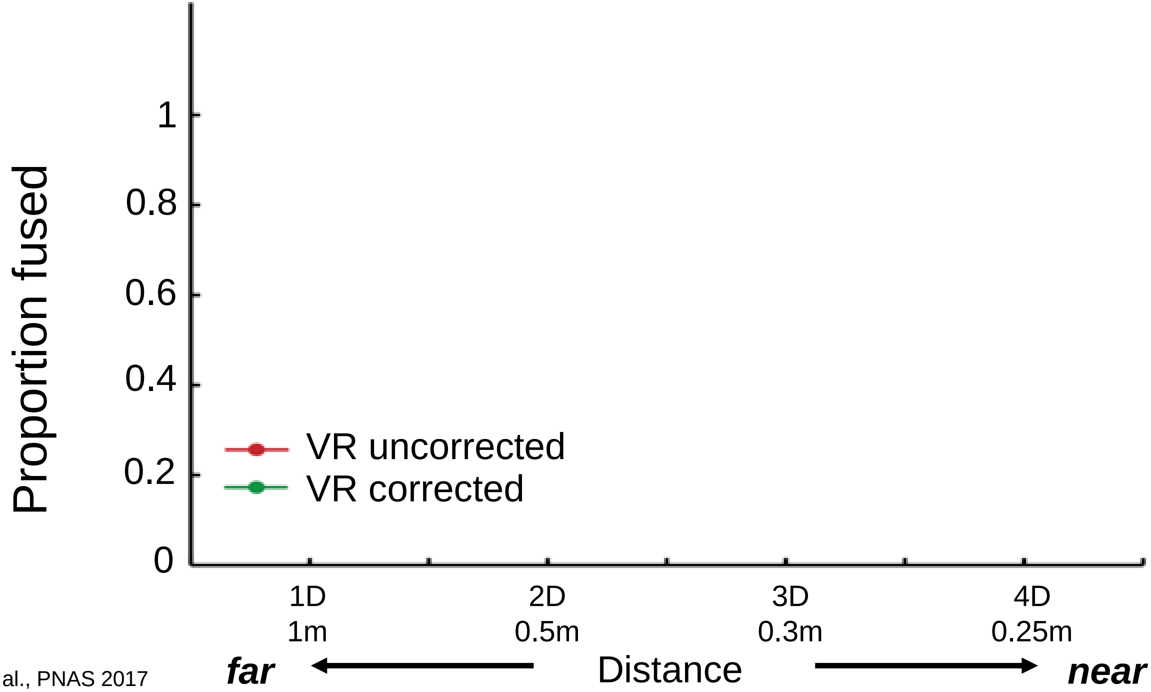


Padmanaban et al., PNAS 2017

Results - Fusion



Padmanaban et al., PNAS 2017

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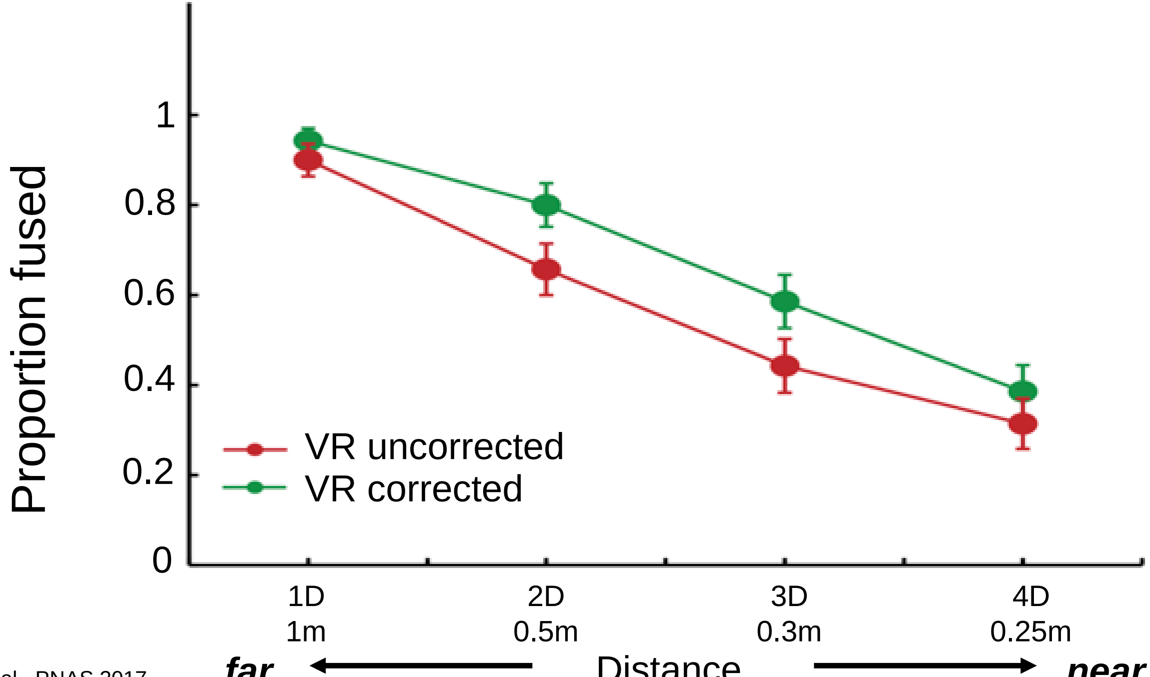

Padmanaban et al., PNAS 2017

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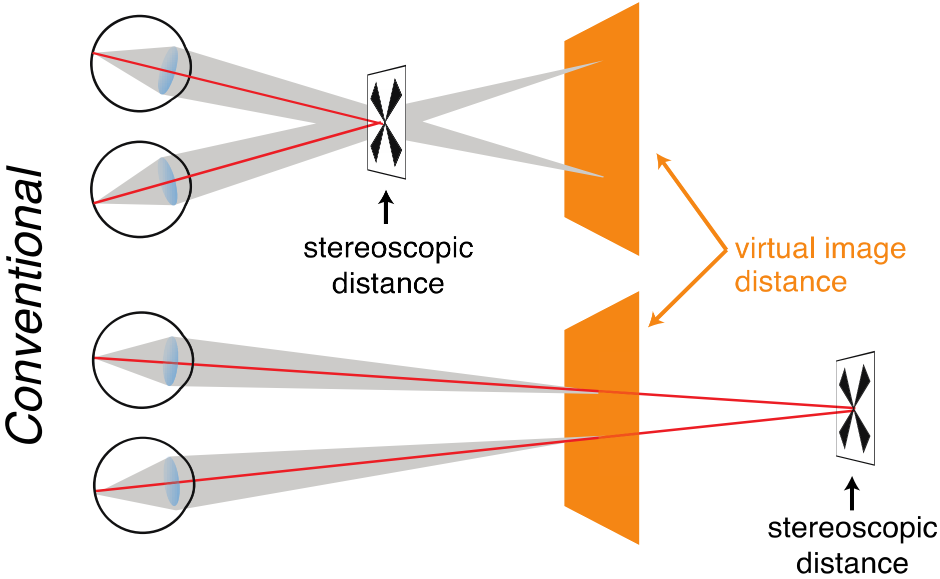
Conventional Stereo / VR Display



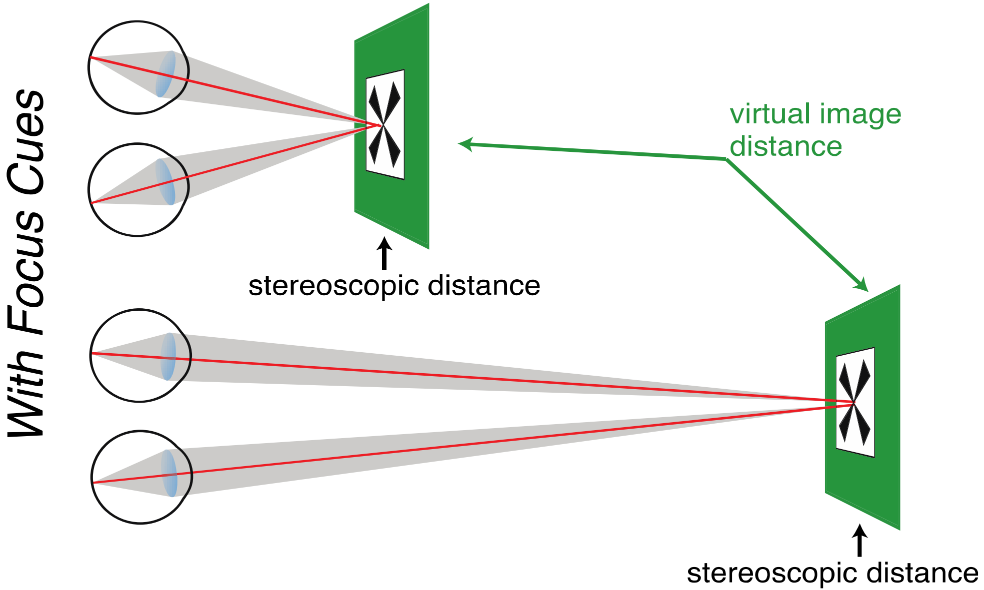
vergence
accommodation

Consequences of Vergence-Accommodation Conflict

- Visual discomfort (eye tiredness & eyestrain) after ~20 minutes of stereoscopic depth judgments (Hoffman et al. 2008; Shibata et al. 2011)

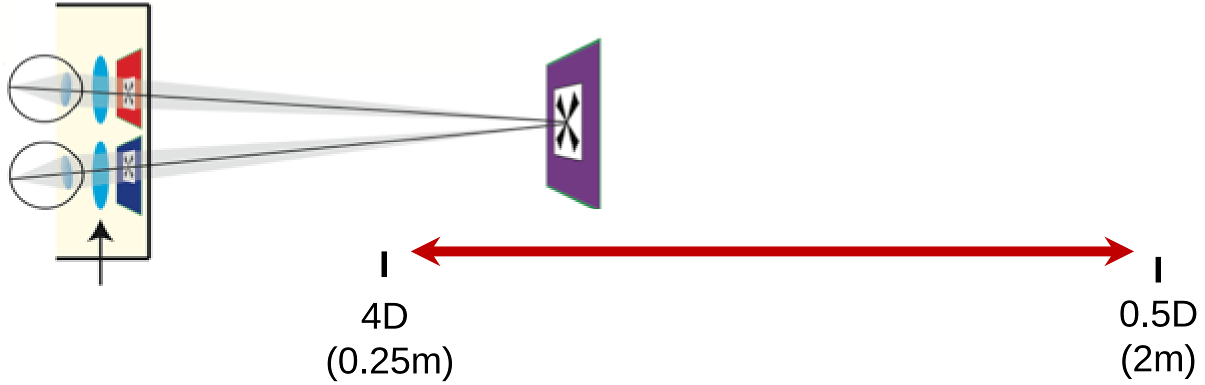
- Degrades visual performance in terms of reaction times and acuity for stereoscopic vision (Hoffman et al. 2008; Konrad et al. 2016; Johnson et al. 2016)

Removing VAC with Adaptive Focus



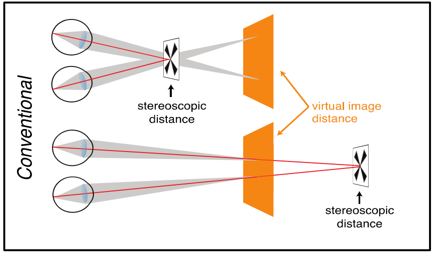
vergence
accommodation

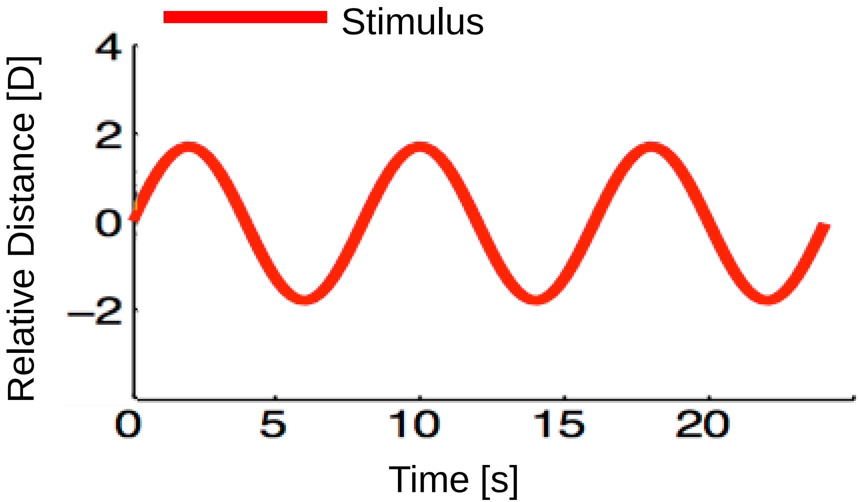
Task



Follow the target with your eyes

Accommodative Response





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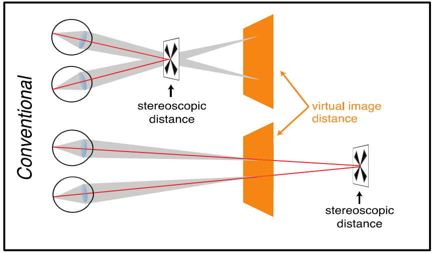
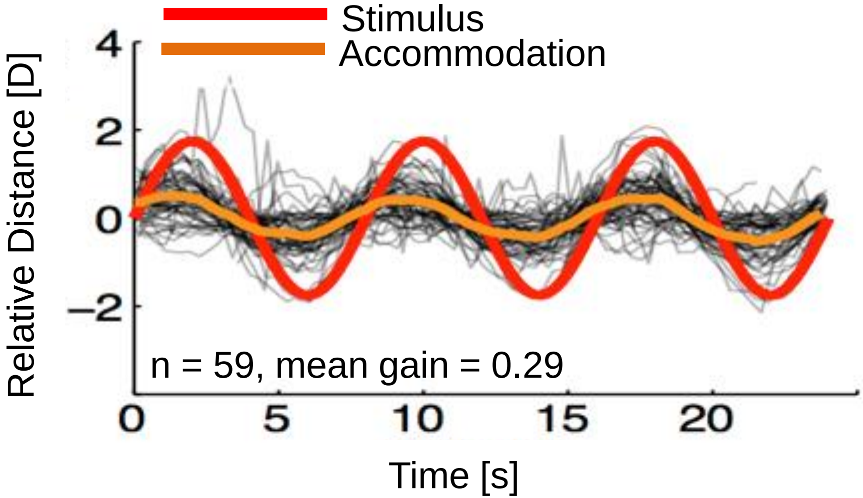
Accommodative Response





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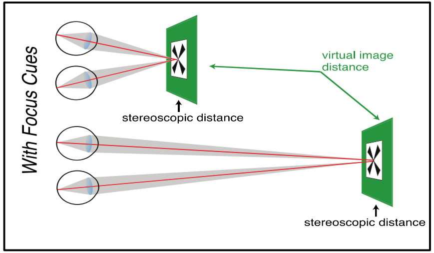
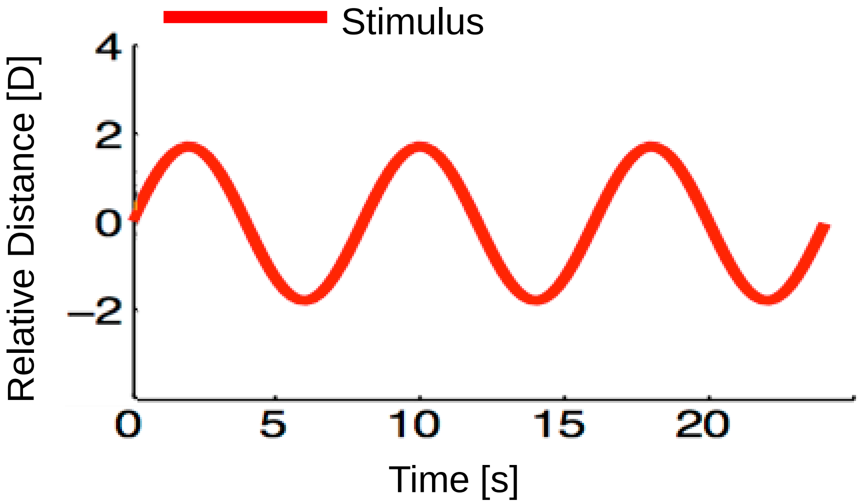
Accommodative Response





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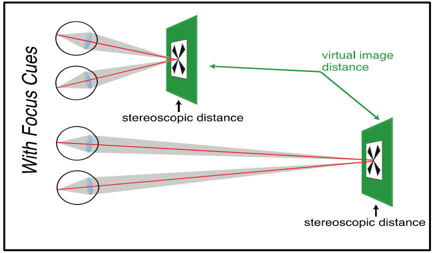
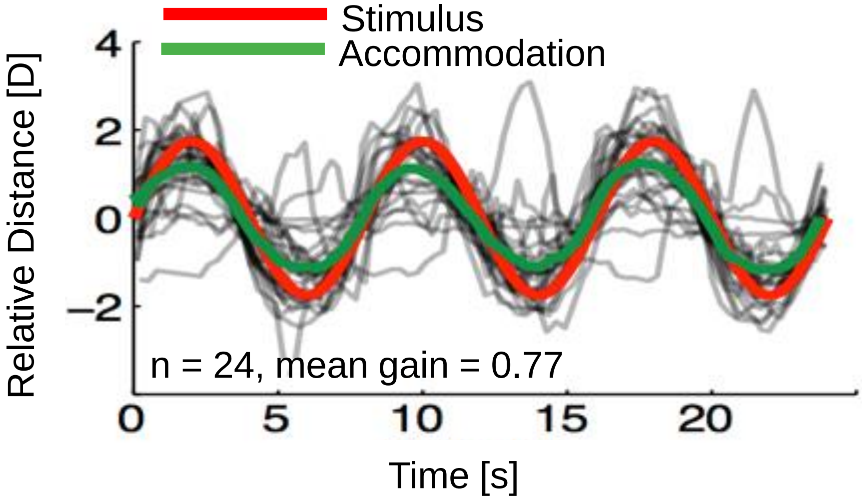
Accommodative Response





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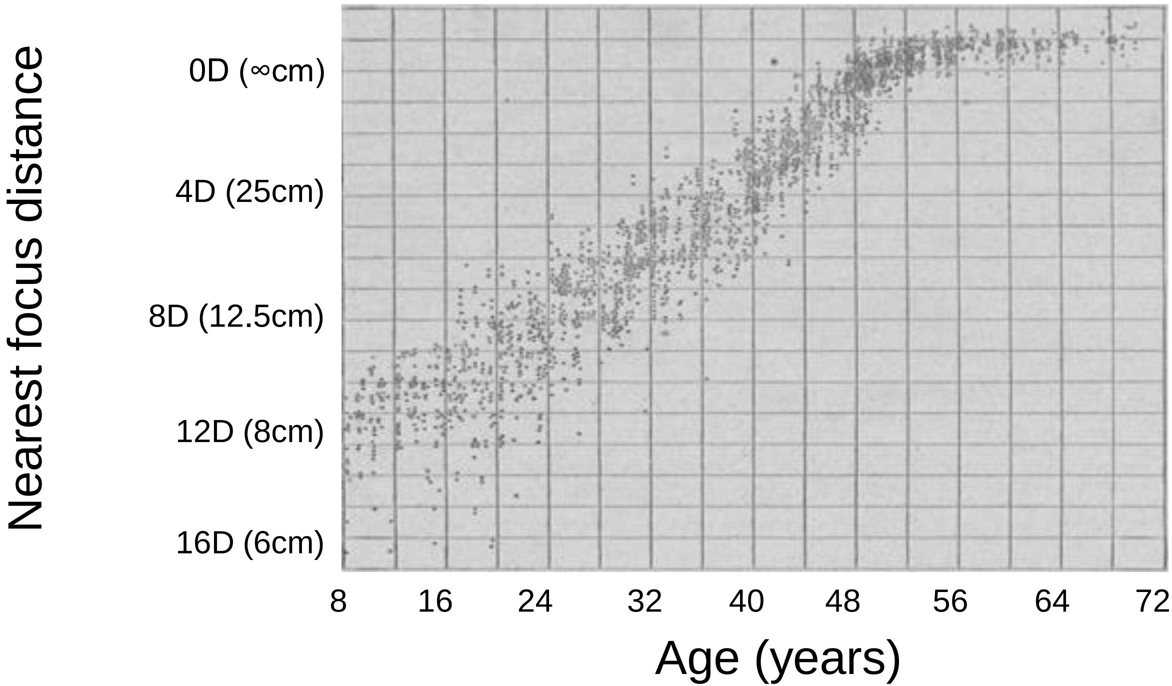
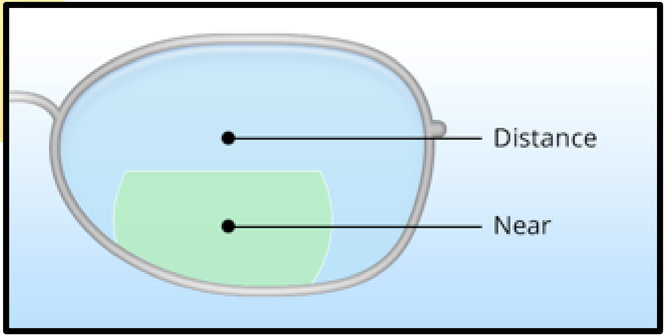
Presbyopia

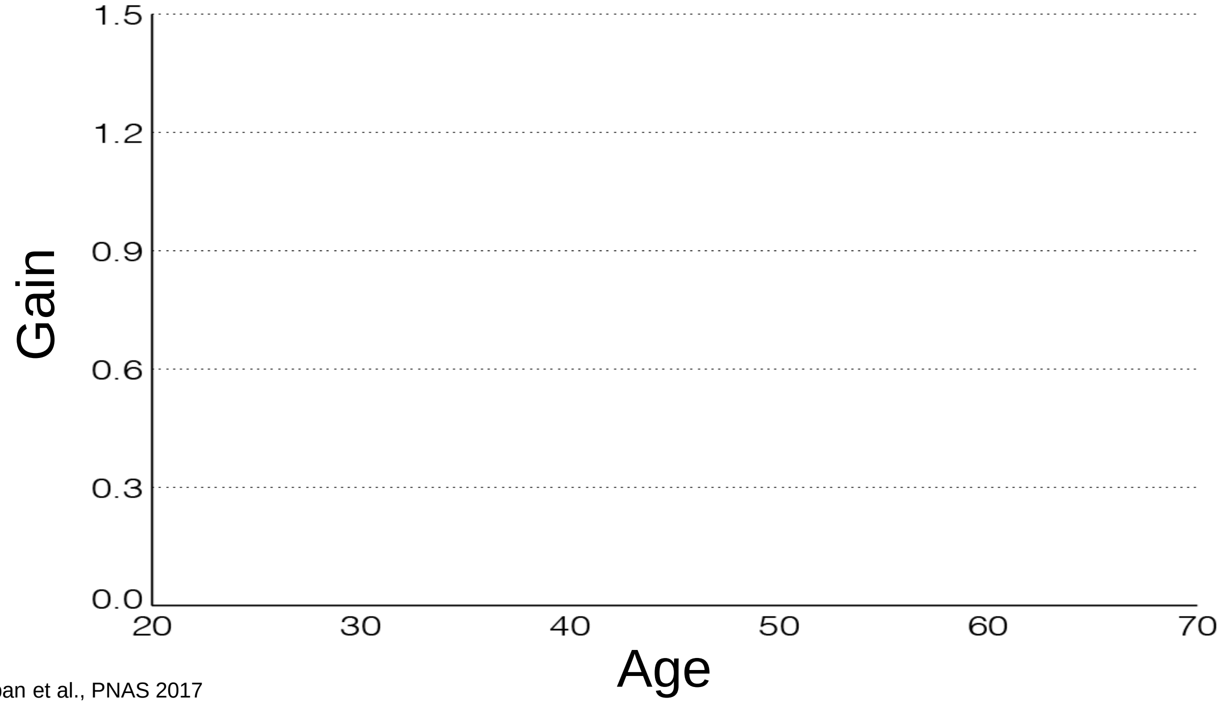


Duane, 1912

Presbyopia



Do Presbyopes Benefit from Dynamic Focus?



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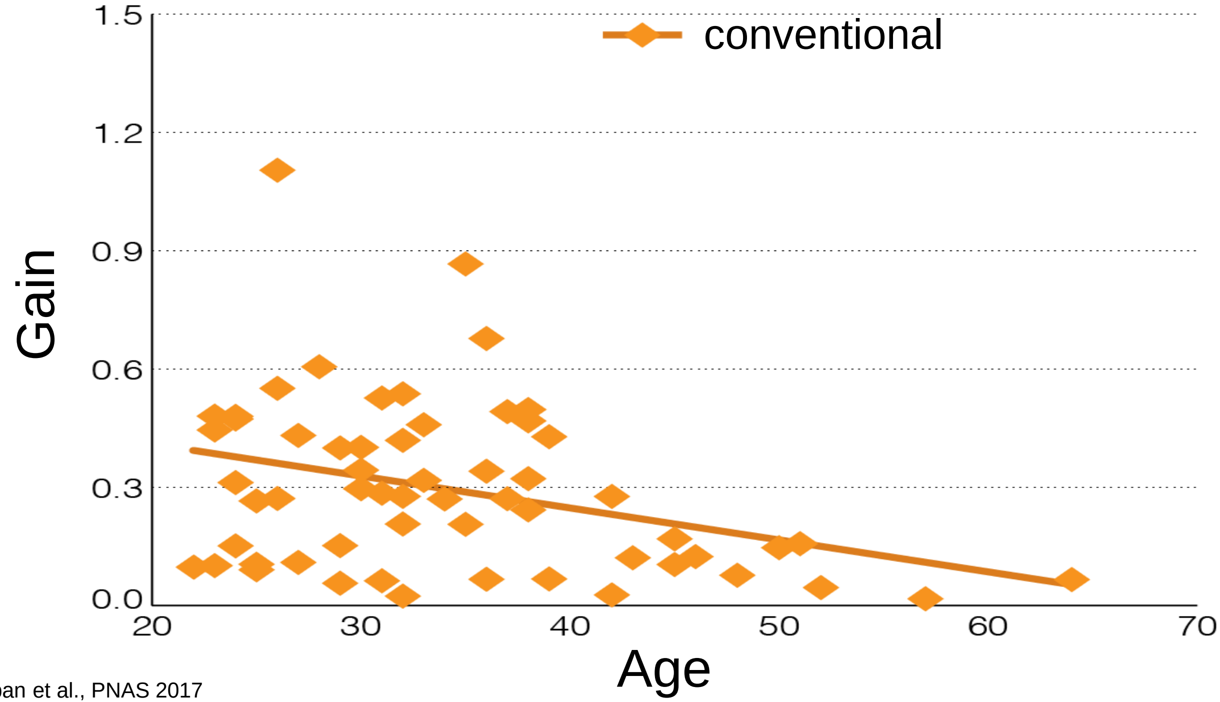

Padmanaban et al., PNAS 2017

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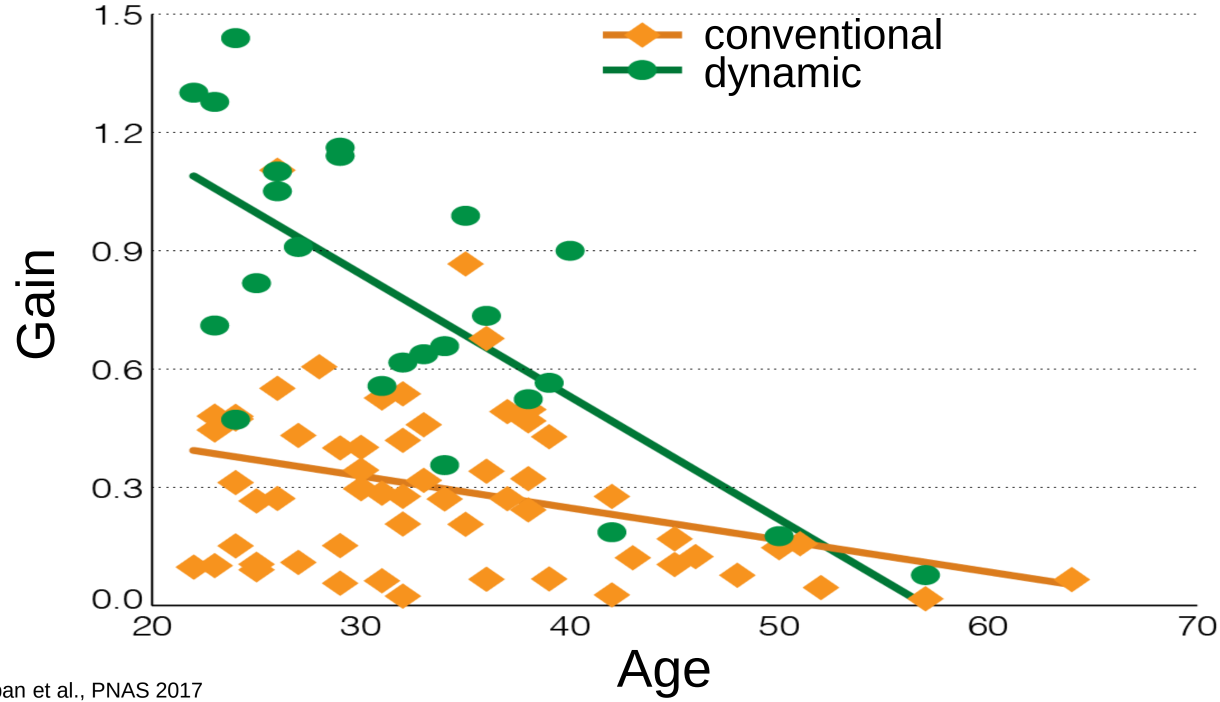

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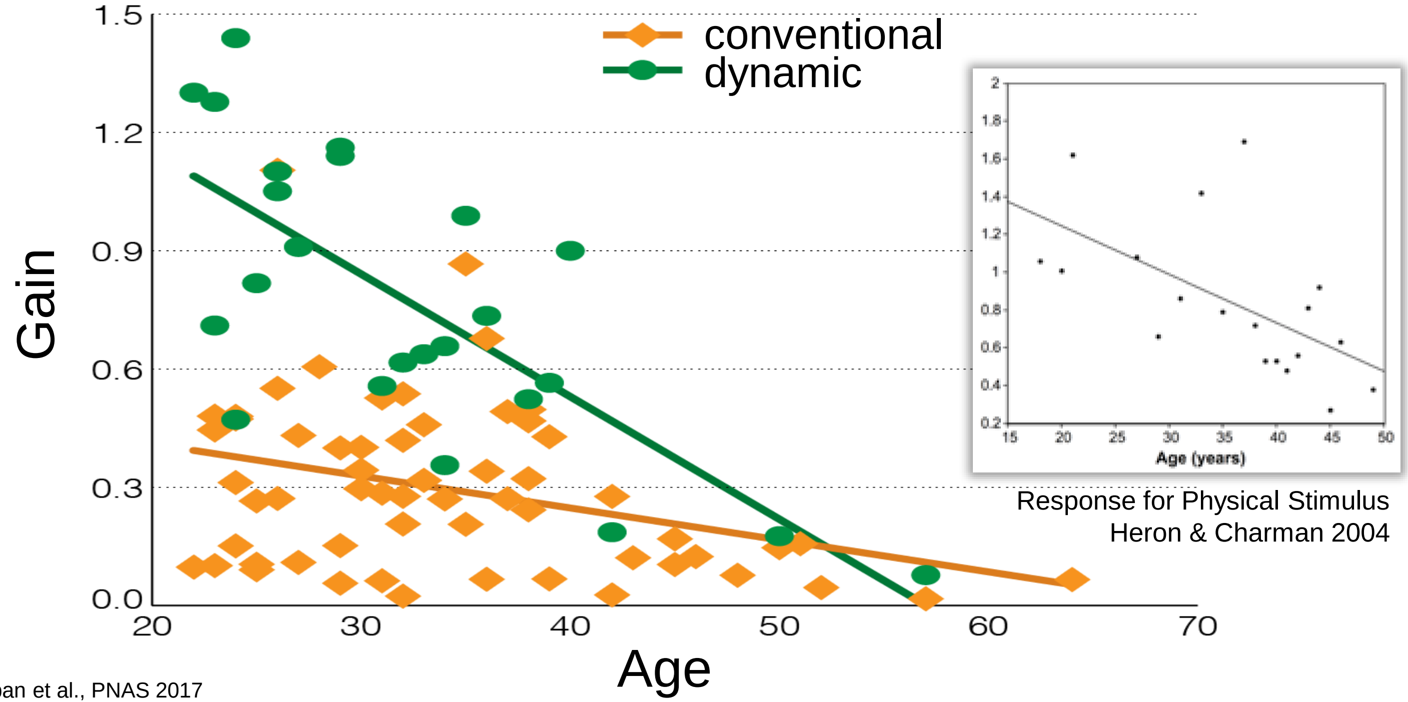
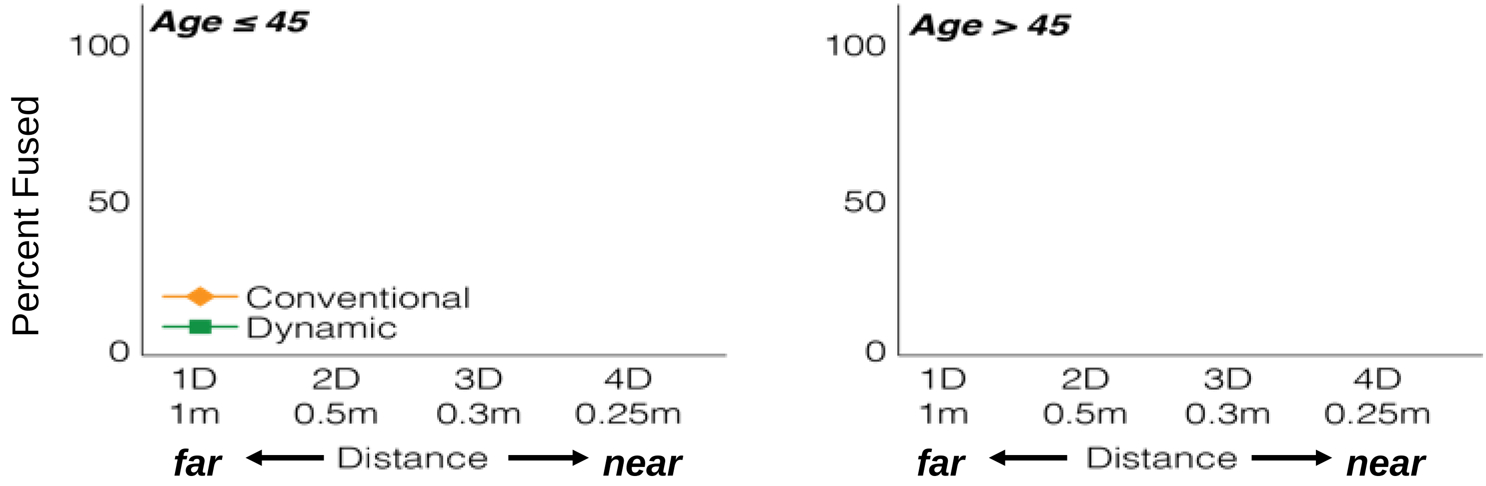


Response for Physical Stimulus
Heron & Charman 2004

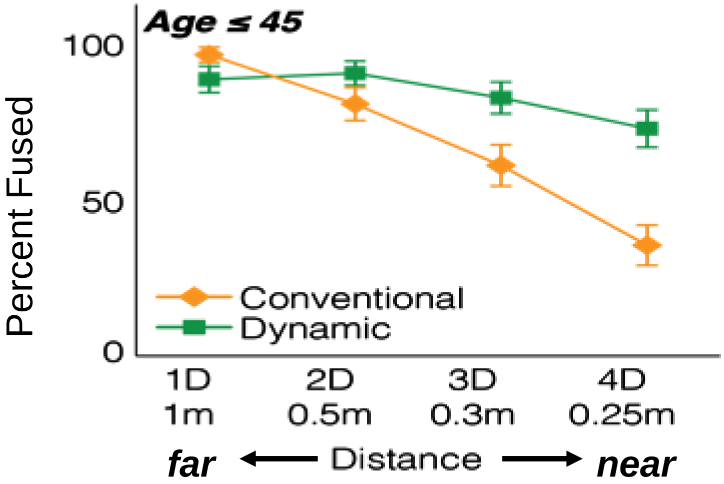
Padmanaban et al., PNAS 2017

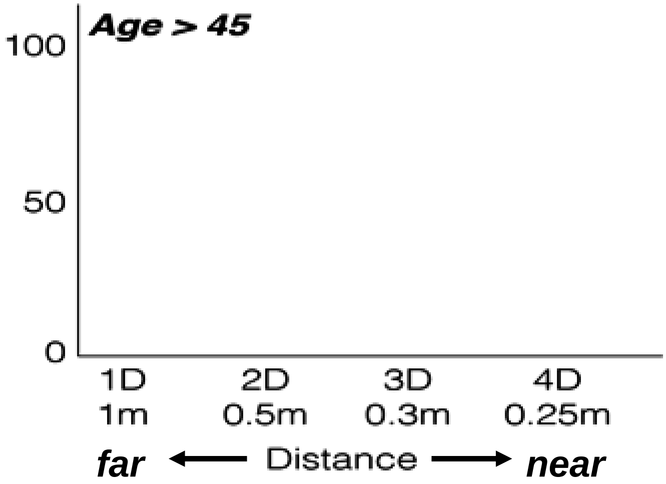
Age-dependent Fusion



Padmanaban et al., PNAS 2017

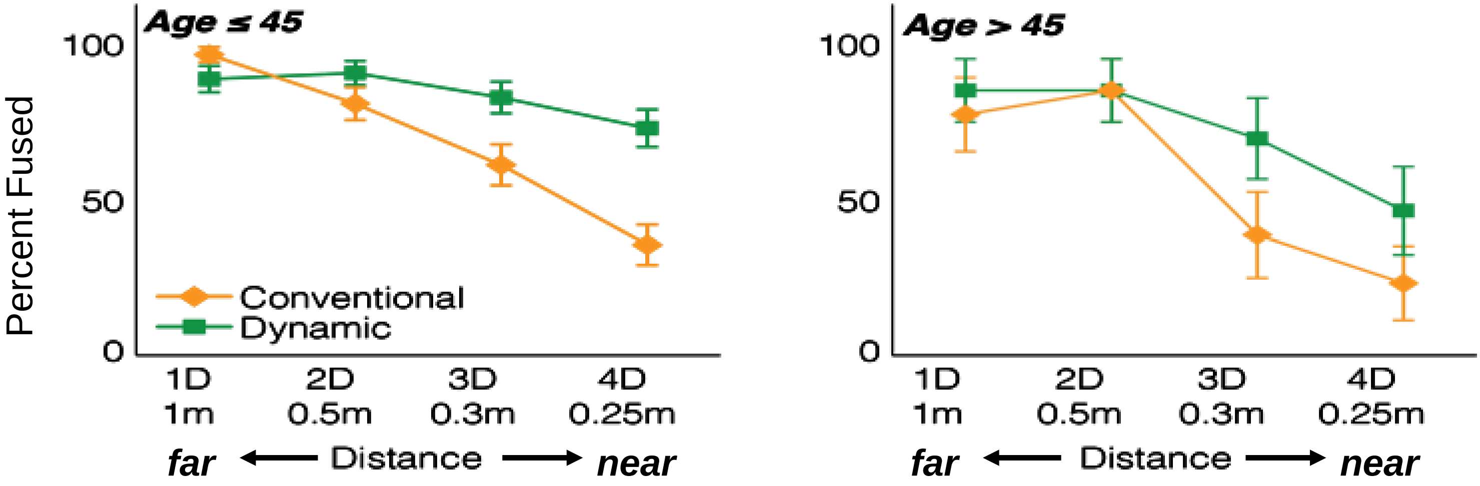
Age-dependent Fusion





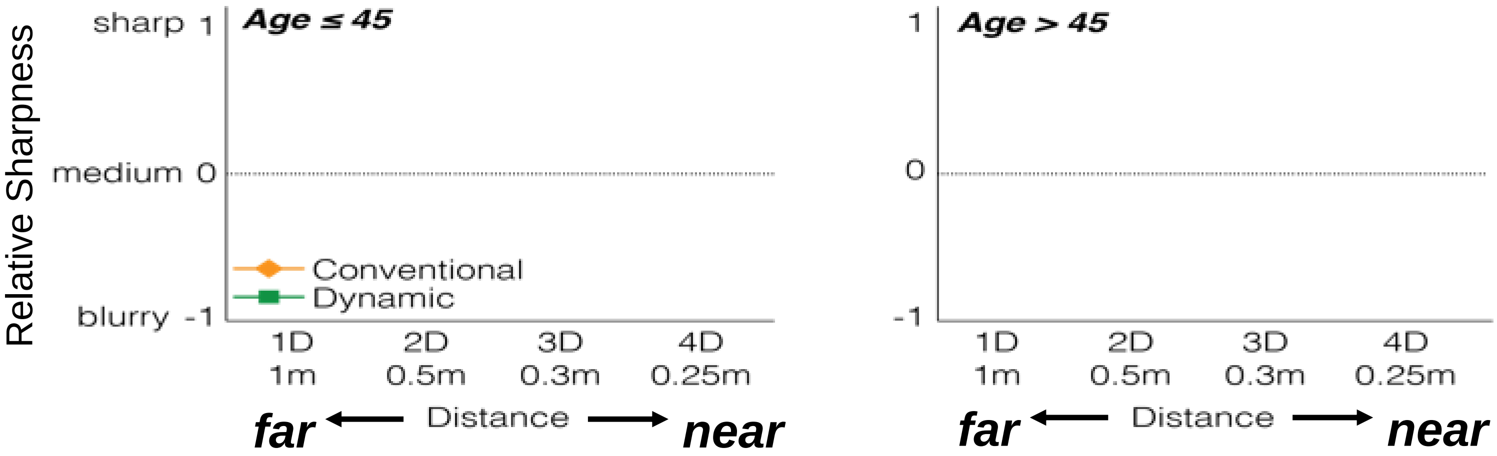
Padmanaban et al., PNAS 2017

Age-dependent Fusion



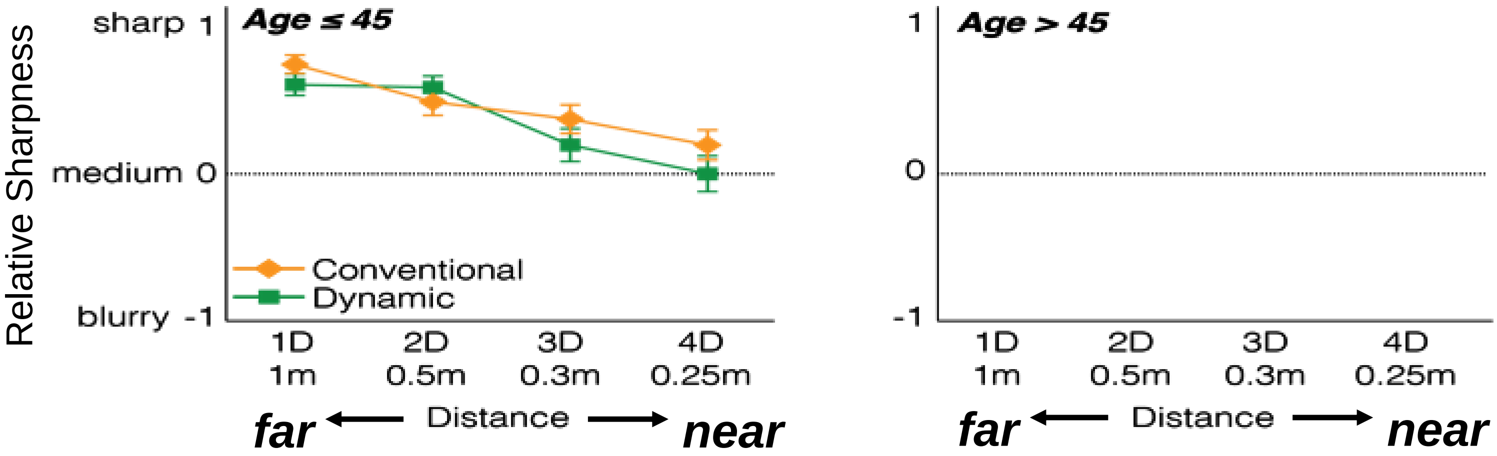
Padmanaban et al., PNAS 2017

Age-dependent Sharpness



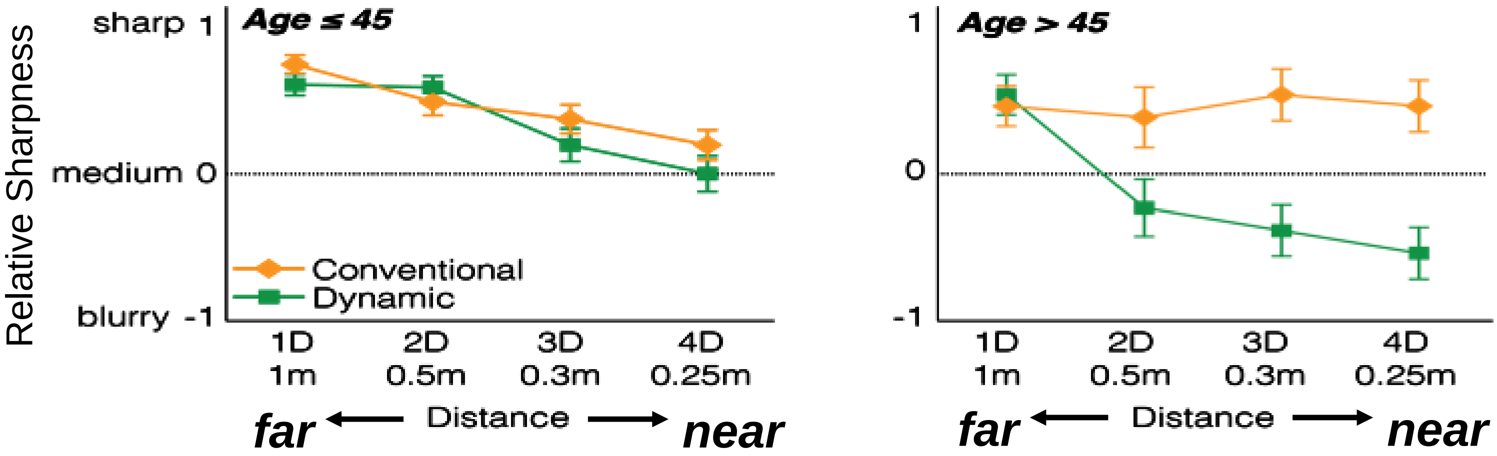
Padmanaban et al., PNAS 2017

Age-dependent Sharpness



Padmanaban et al., PNAS 2017

Age-dependent Sharpness



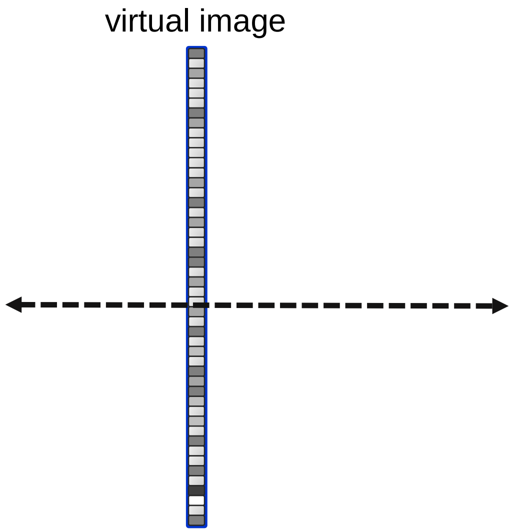
Padmanaban et al., PNAS 2017

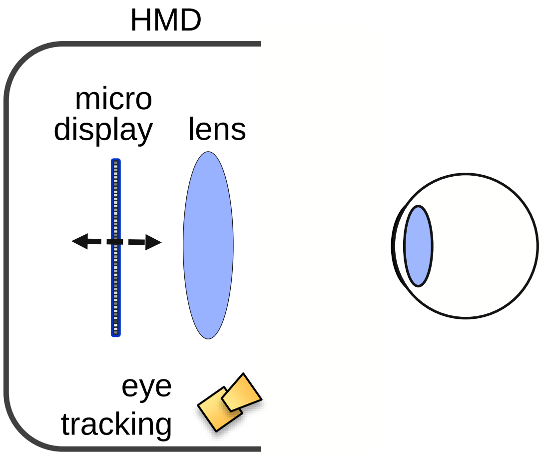
- Q1: Can computational displays effectively replace glasses in VR/AR?
- Q2: How to address the vergence-accommodation conflict for users of different ages?
- Q3: What are (in)effective near-eye display technologies?

possible solutions: gaze-contingent focus, monovision, multiplane, light field displays, …

Gaze-contingent Focus

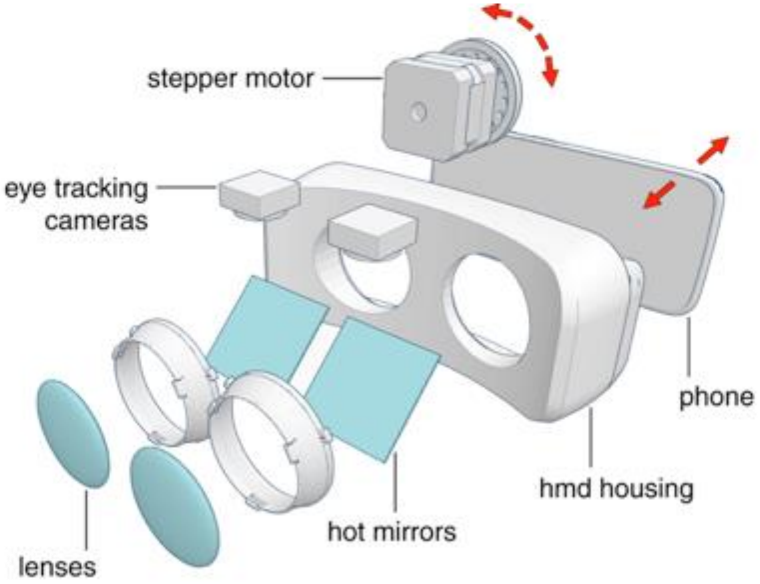
- <u>non-presbyopes</u>: adaptive focus is <u>like real world</u>, but needs eye tracking!





Padmanaban et al., PNAS 2017

Gaze-contingent Focus



Padmanaban et al., PNAS 2017

Gaze-contingent Focus

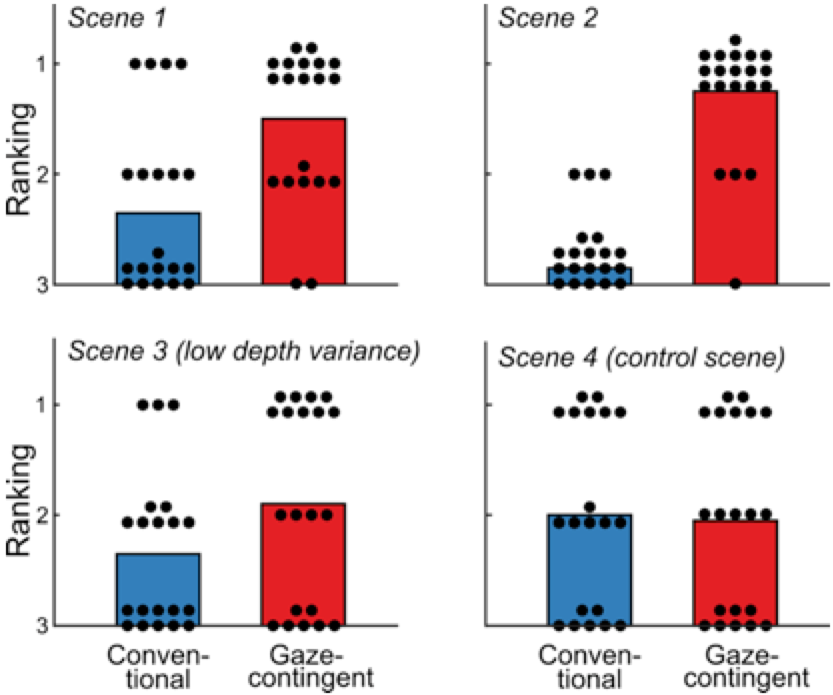
Padmanaban et al., PNAS 2017

Gaze-contingent Focus

Padmanaban et al., PNAS 2017

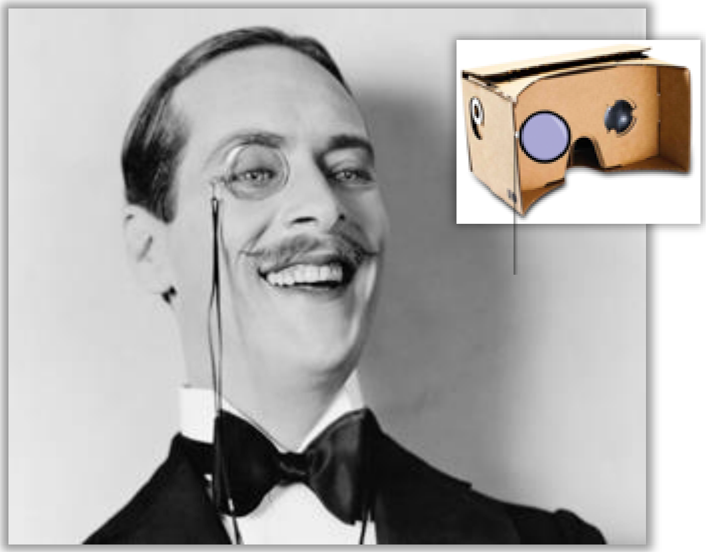
at ACM SIGGRAPH 2016

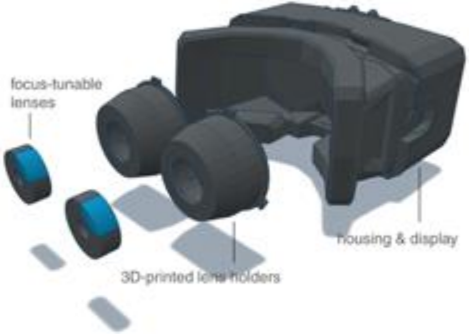
Gaze-contingent Focus – User Preference



Padmanaban et al., PNAS 2017

Monovision VR

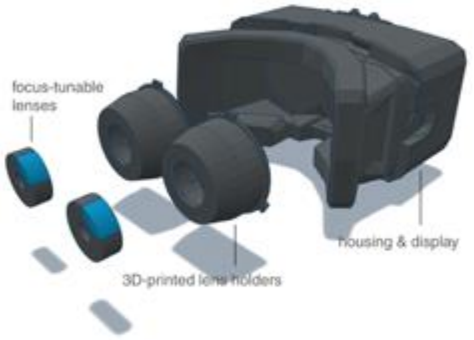


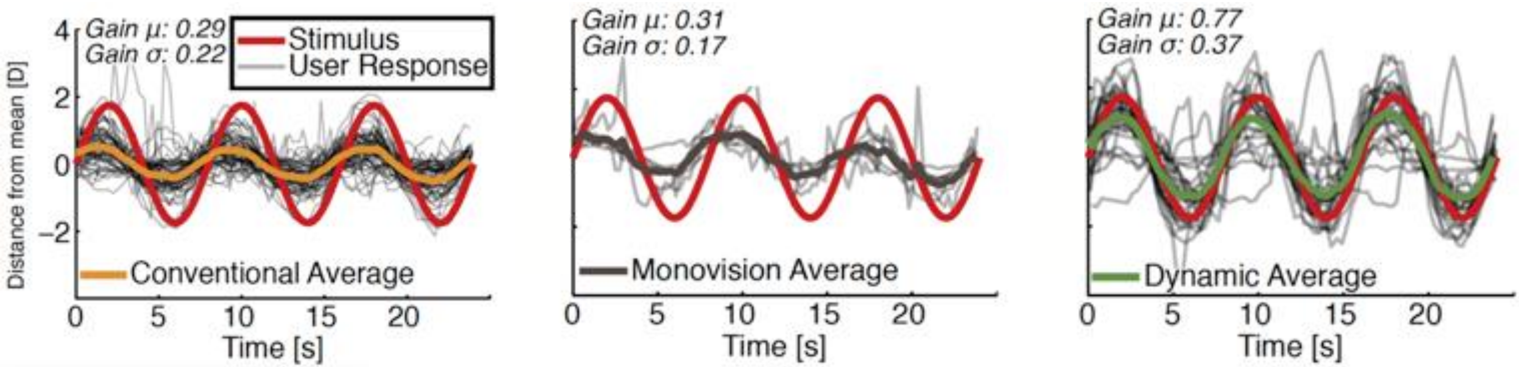


Konrad et al., SIGCHI 2016; Johnson et al., Optics Express 2016; Padmanaban et al., PNAS 2017

Monovision VR

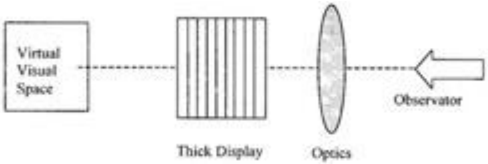
- monovision did not drive accommodation more than conventional
- visually comfortable for most; particularly uncomfortable for some users





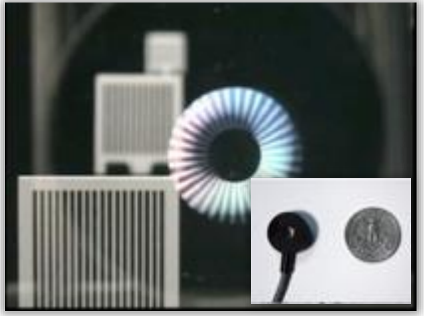
Konrad et al., SIGCHI 2016; Johnson et al., Optics Express 2016; Padmanaban et al., PNAS 2017

Multiplane VR Displays



idea introduced
Rolland et al. 2000

benchtop prototype
Akeley 2004



near-eye display prototype
Liu 2008, Love 2009

- Rolland J, Krueger M, Goon A (2000) Multifocal planes head-mounted displays. Applied Optics 39
- Akeley K, Watt S, Girshick A, Banks M (2004) A stereo display prototype with multiple focal distances. ACM Trans. Graph. (SIGGRAPH)
- Waldkirch M, Lukowicz P, Tröster G (2004) Multiple imaging technique for extending depth of focus in retinal displays. Optics Express
- Schowengerdt B, Seibel E (2006) True 3-d scanned voxel displays using single or multiple light sources. JSID
- Liu S, Cheng D, Hua H (2008) An optical see-through head mounted display with addressable focal planes in Proc. ISMAR
- Love GD et al. (2009) High-speed switchable lens enables the development of a volumetric stereoscopic display. Optics Express
- … many more ...

Multiplane VR Displays

idea introduced
Rolland et al. 2000

benchtop prototype
Akeley 2004

near-eye display prototype
Liu 2008, Love 2009

biggest problem: flicker

- Rolland J, Krueger M, Goon A (2000) Multifocal planes head-mounted displays. Applied Optics 39
- Akeley K, Watt S, Girshick A, Banks M (2004) A stereo display prototype with multiple focal distances. ACM Trans. Graph. (SIGGRAPH)
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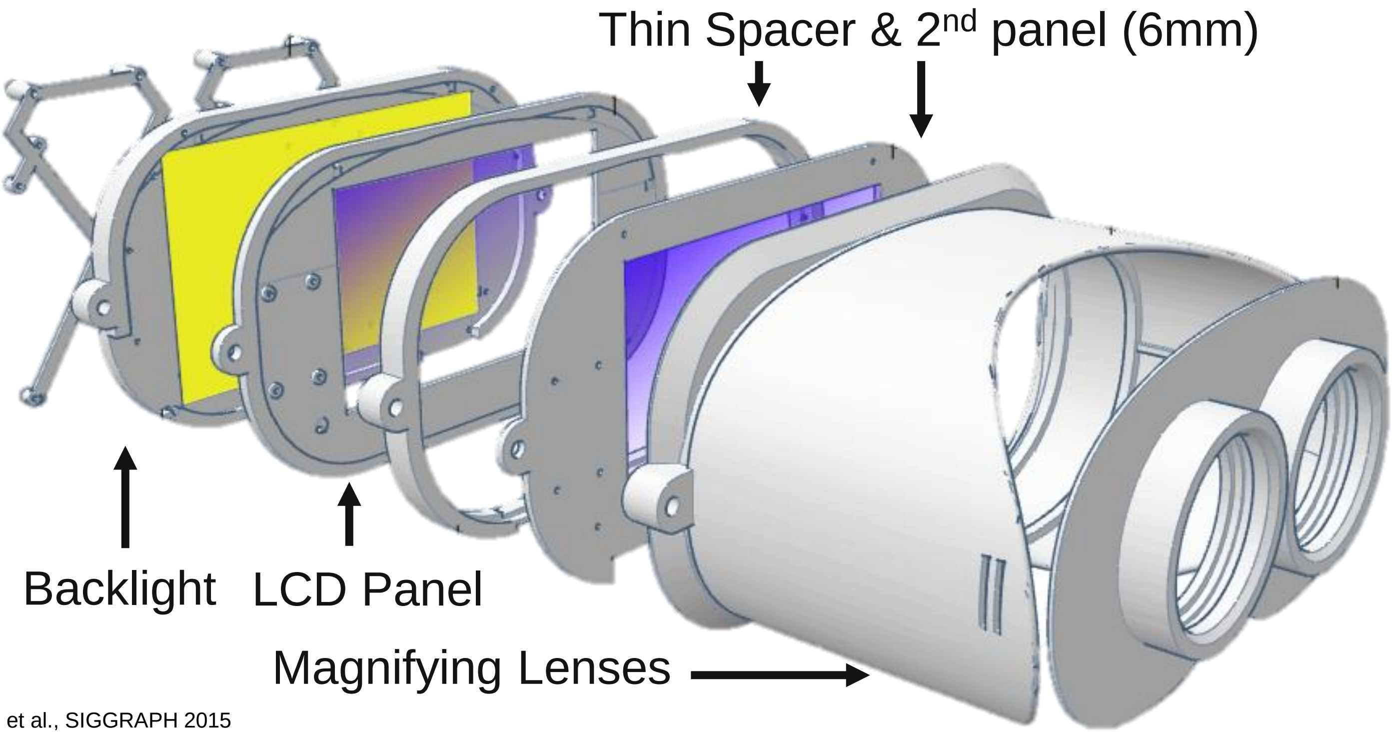
Light Field Stereoscope

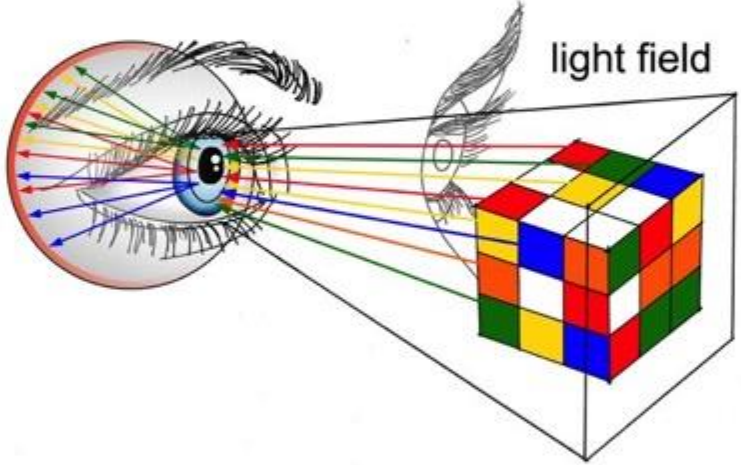
Huang et al., SIGGRAPH 2015

Light Field Stereoscope

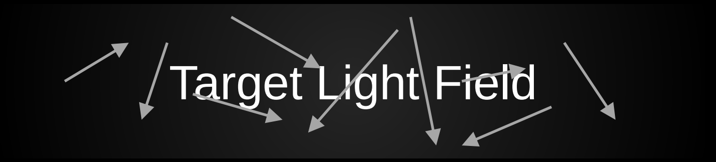


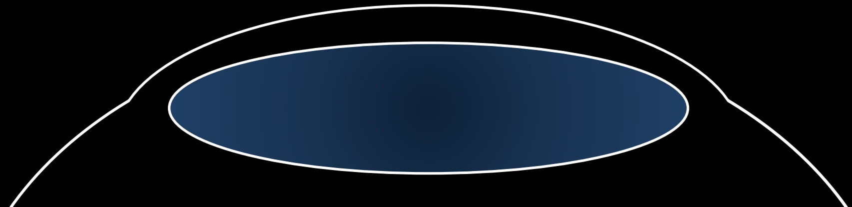
Huang et al., SIGGRAPH 2015

Near-eye Light Field Displays



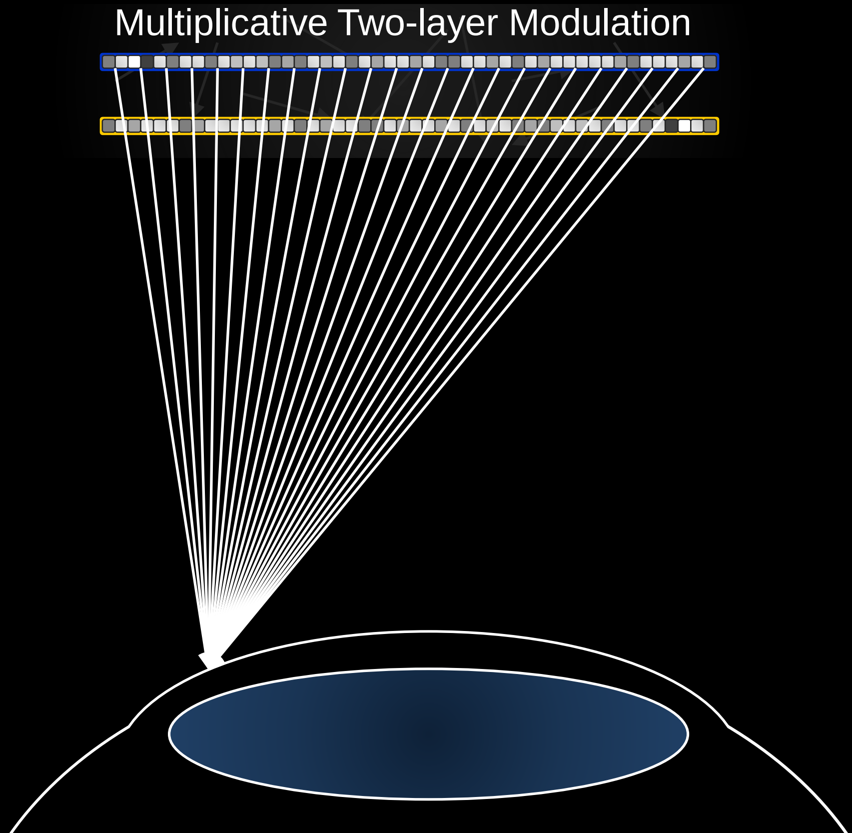
Idea: project multiple different perspectives into different parts of the pupil!





Input: 4D light field for each eye

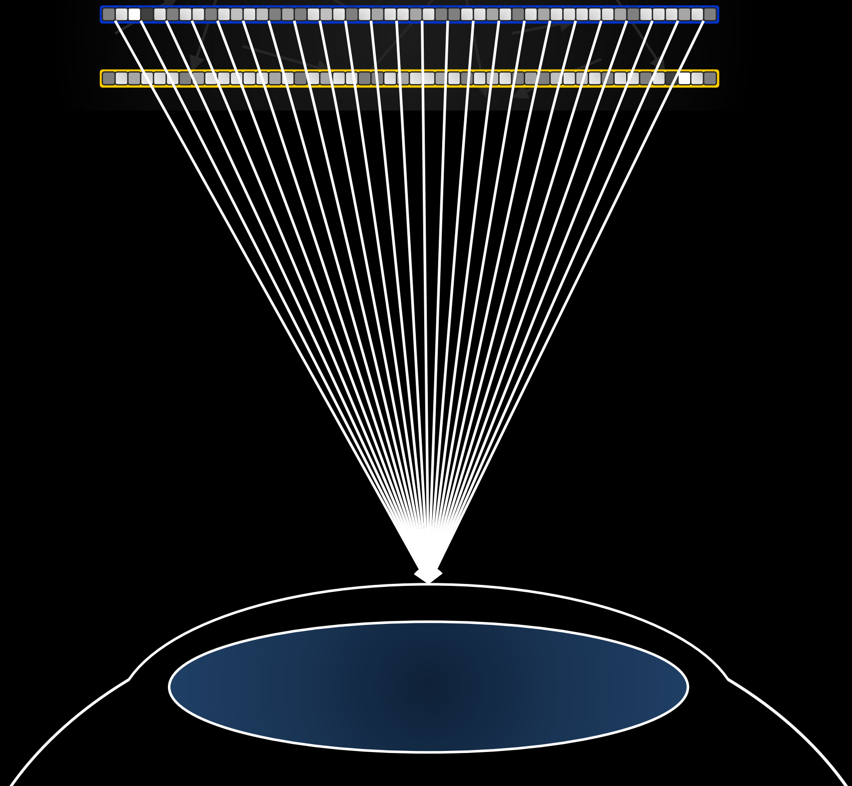
Model Courtesy of Bushmills Irish Whiskey



Input: 4D light field for each eye

Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation



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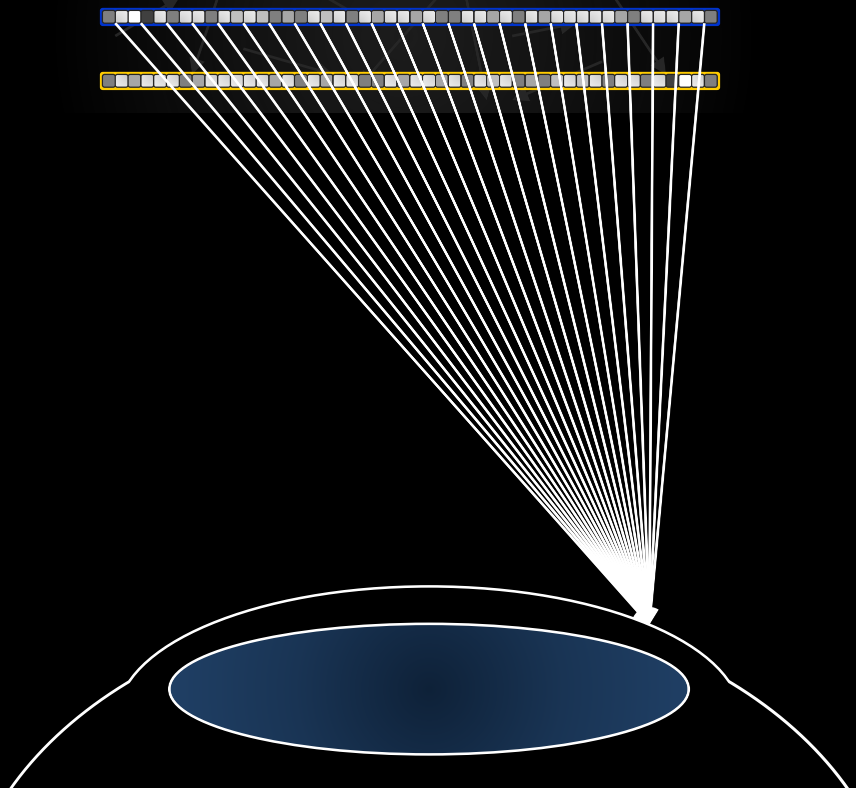
Multiplicative Two-layer Modulation



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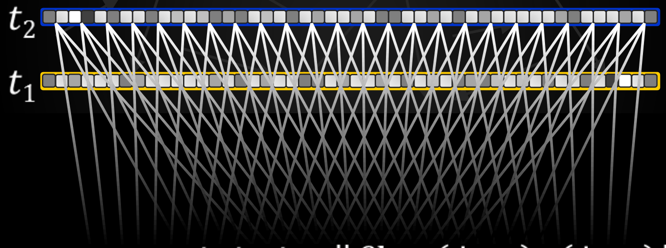
Multiplicative Two-layer Modulation



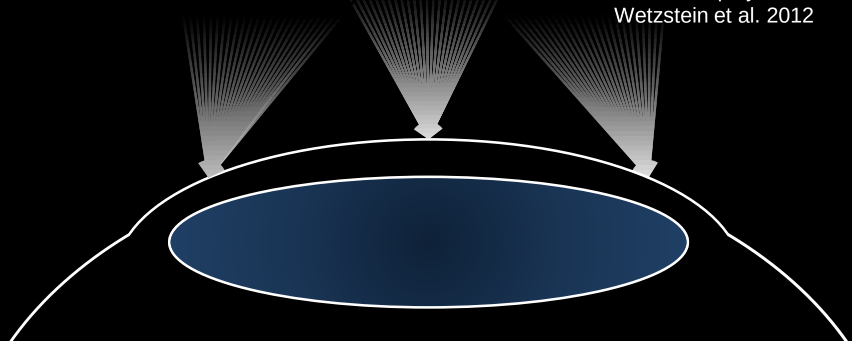
$$\underset{\{t_1, t_2\}}{minimize} \; \|\beta \mathrm{l} - (\phi_1 t_1) \circ (\phi_2 t_2)\|^2 \quad s.t. \; 0 \leq \; t_1, t_2 \leq 1$$

Reconstruction:

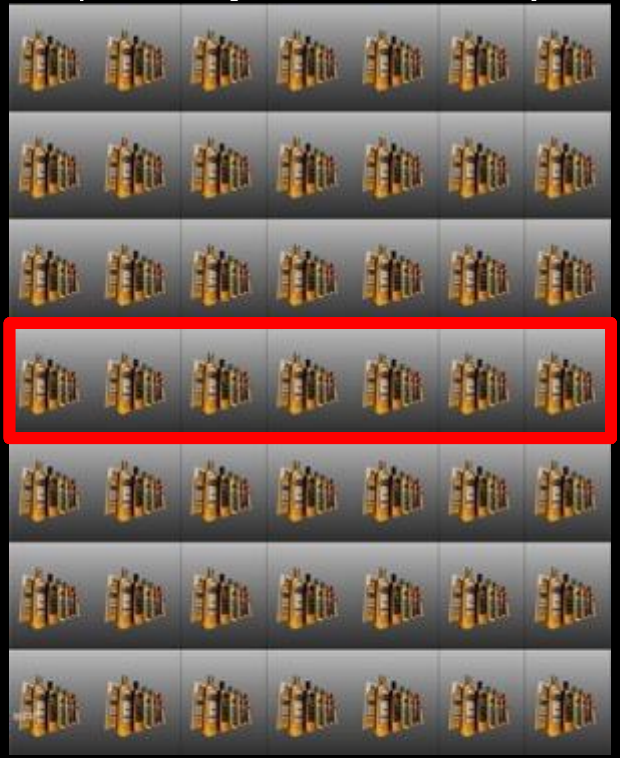
$$t_1 \leftarrow t_1 \circ \frac{\phi_1^T(\beta \mathrm{l} \circ (\phi_2 t_2))}{\phi_1^T\left(\tilde{\mathrm{l}} \circ (\phi_2 t_2)\right) + \epsilon}$$

for layer t_1

Tensor Displays, Wetzstein et al. 2012

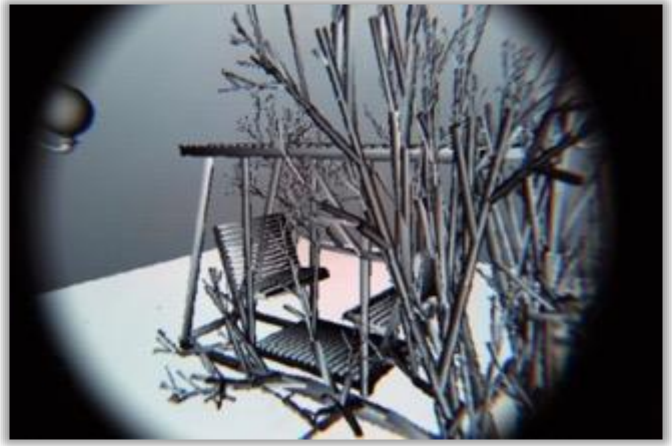


Input: 4D light field for each eye



Model Courtesy of Bushmills Irish Whiskey

Light Field Stereoscope

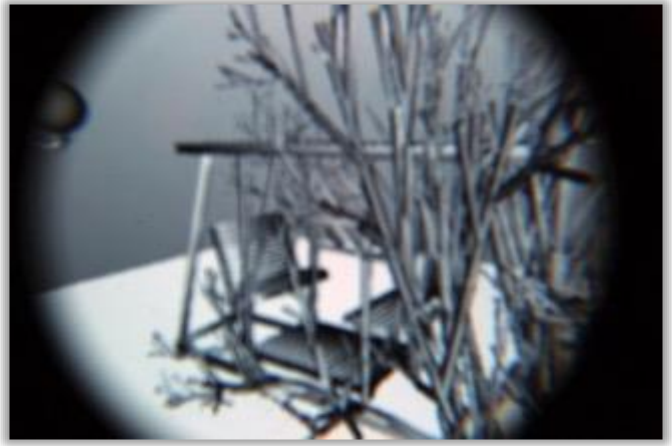


Traditional HMDs
- No Focus Cues

The Light Field HMD
Stereoscope

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



Traditional HMDs
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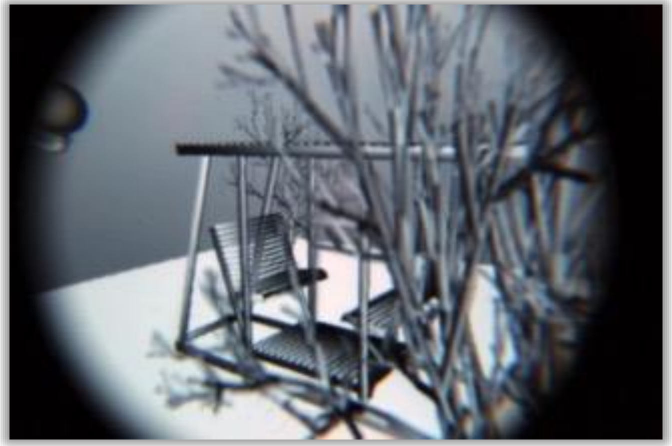

The Light Field HMD
Stereoscope

Huang et al., SIGGRAPH 2015

Light Field Stereoscope

Traditional HMDs
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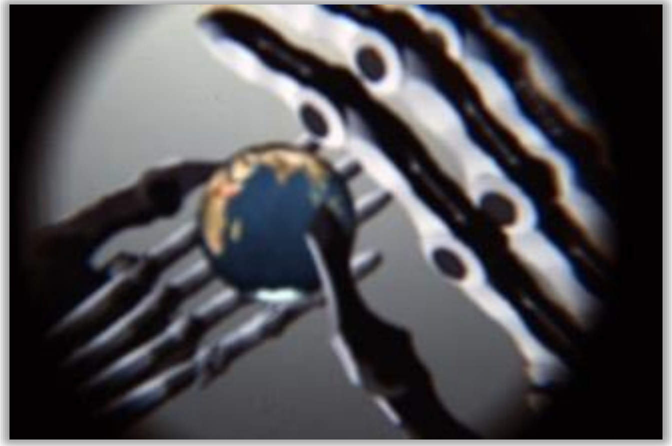
Stereoscope

Model Courtesy of Paul H. Manning

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



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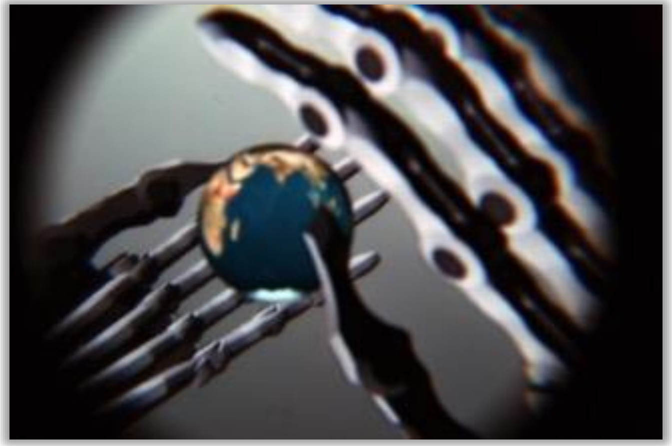
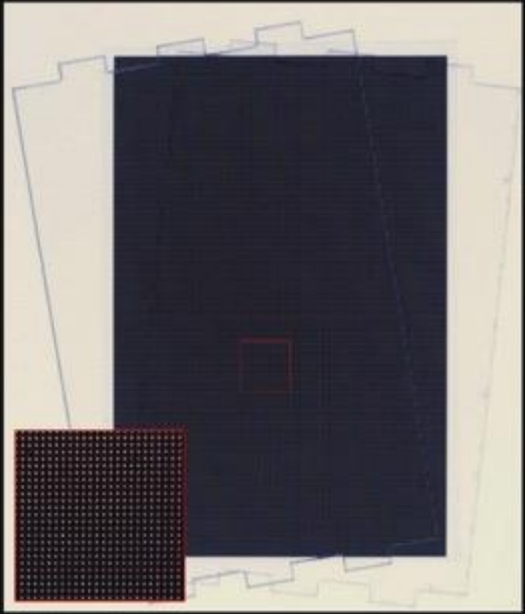


The Light Field HMD
Stereoscope

Model Courtesy of Paul H. Manning

Huang et al., SIGGRAPH 2015

Vision-correcting Display



printed transparency

iPod Touch prototype

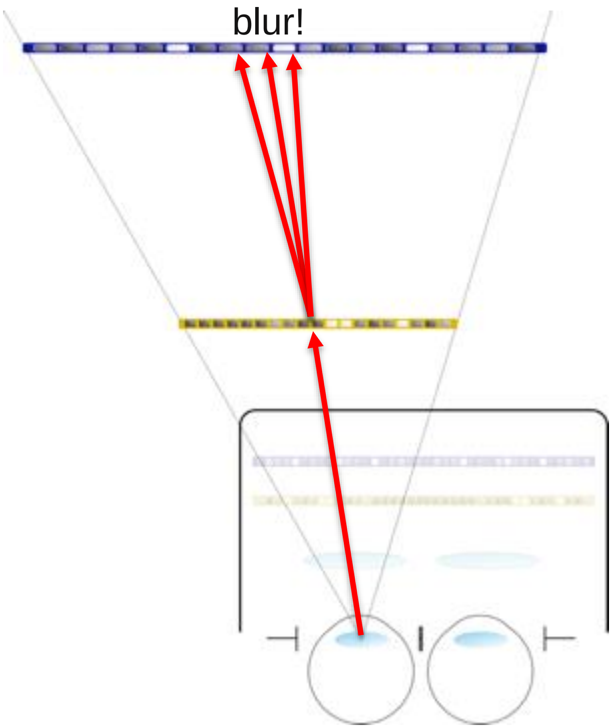
Huang et al., SIGGRAPH 2014

prototype

300 dpi or higher

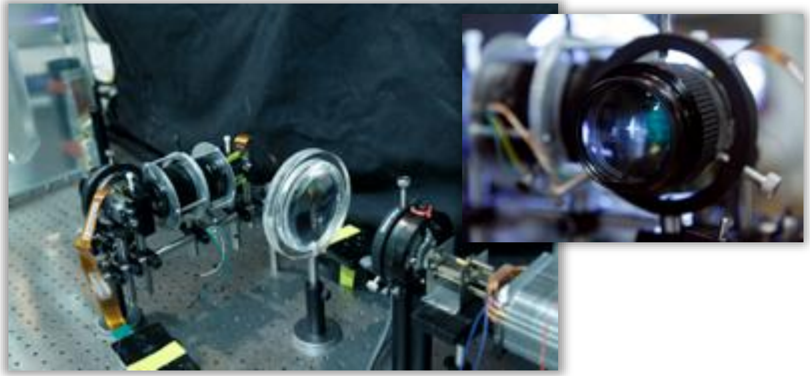
Huang et al., SIGGRAPH 2014

Diffraction in Multilayer Light Field Displays



Wetzstein et al., SIGGRAPH 2011
Lanman et al., SIGGRAPH Asia 2011
Wetzstein et al., SIGGRAPH 2012
Maimone et all., Trans. Graph. 2013
…

No diffraction artifacts with LCoS



Hirsch et al, SIGGRAPH 2014

Summary

- focus cues in VR/AR are challenging
- adaptive focus can correct for refractive errors (myopia, hyperopia)
- gaze-contingent focus gives natural focus cues for non-presbyopes, but require eyes tracking
- presbyopes require fixed focal plane with correction
- multiplane displays require very high speed microdisplays
- monovision has not demonstrated significant improvements
- light field displays may be the “ultimate” display → need to solve “diffraction problem”

Making Virtual Reality Better Than Reality?

- focus cues in VR/AR are challenging
- adaptive focus can correct for refractive errors (myopia, hyperopia)
- gaze-contingent focus gives natural focus cues for non-presbyopes, but require eyes tracking
- presbyopes require fixed focal plane with correction, better than reality!
- multiplane displays require very high speed microdisplays
- monovision has not demonstrated significant improvements
- light field displays may be the "ultimate" display → need to solve "diffraction problem"

VR/AR = Frontier of Engineering

- Focus cues / visual accessibility
- Vestibular-visual conflict (motion sickness)

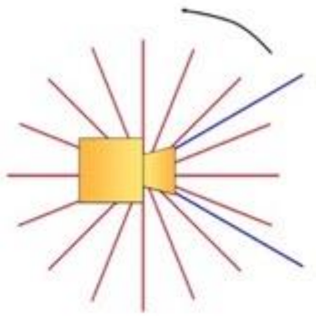
- AR
  - occlusions
  - aesthetics / form factor
  - battery life
  - heat
  - wireless operation
  - low-power computer vision
  - registration of physical / virtual world and eyes
  - consistent lighting
  - scanning real world
  - VAC more important
  - display contrast & brightness
  - fast, embedded GPUs
  - …

Capturing and Sharing Experiences

It’s Not About Technology but Experiences!

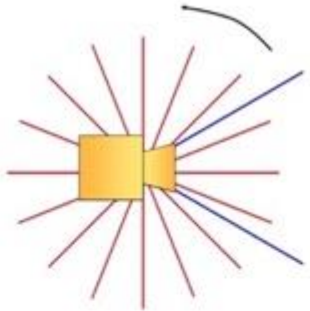
Panorama

mono & head orientation



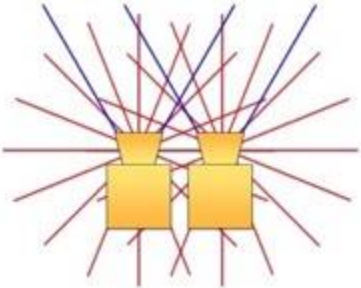
Ricoh Theta

Panorama
mono & head orientation

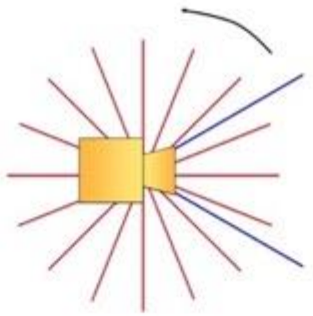


Ricoh Theta

Stereo Panorama
stereo & no head orientation

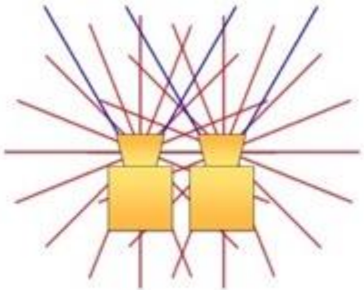


Panorama
mono & head orientation

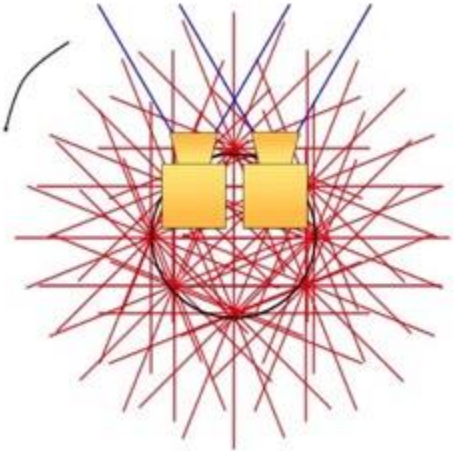


Ricoh Theta

Stereo Panorama
stereo & no head orientation

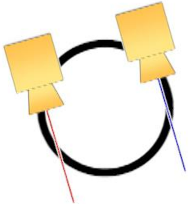


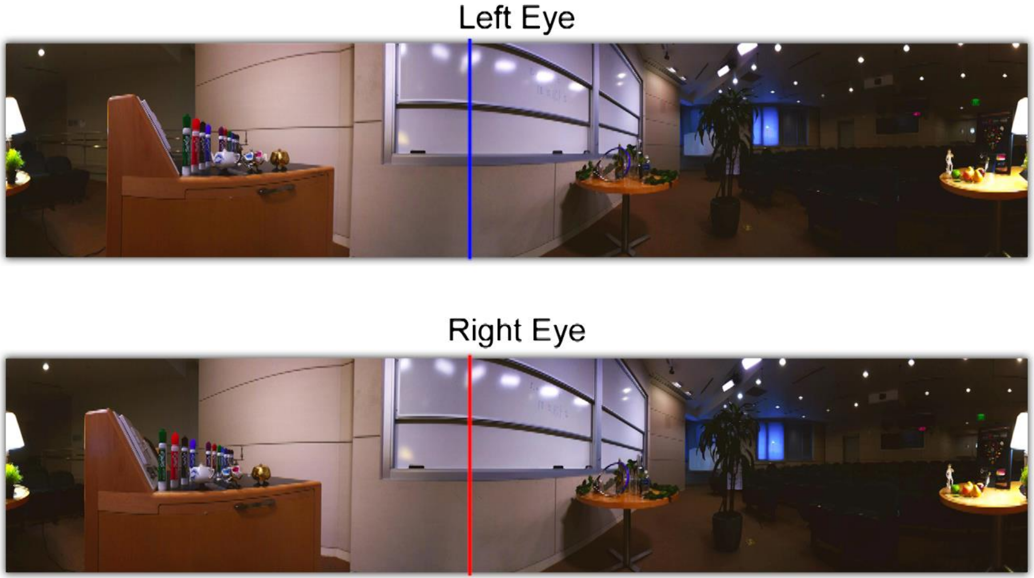
Omnidirectional Stereo
stereo & head orientation



Google Jump

Omnidirectional Stereo





widely used by YouTube VR, Google Daydream, Facebook, ...

Existing VR Cameras

Recorded Videos ~ 17 Gb/sec

Facebook’s Surround 360

RAW Data: 17 Gb/sec

Compute time: days to weeks on conventional computer,
minutes to hours on data center

Facebook's Surround 360

RAW Data: 17 Gb/sec

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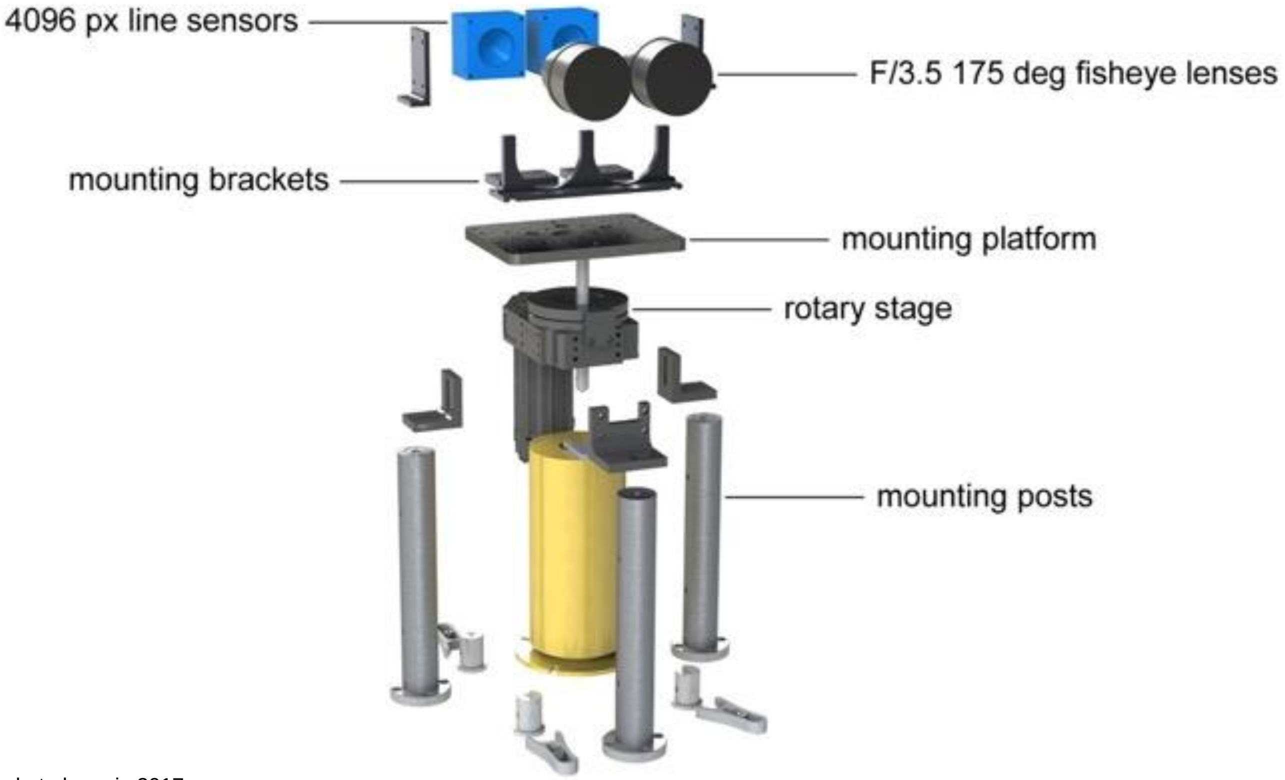
Konrad et al., arxiv 2017

Konrad et al., arxiv 2017



Konrad et al., arxiv 2017

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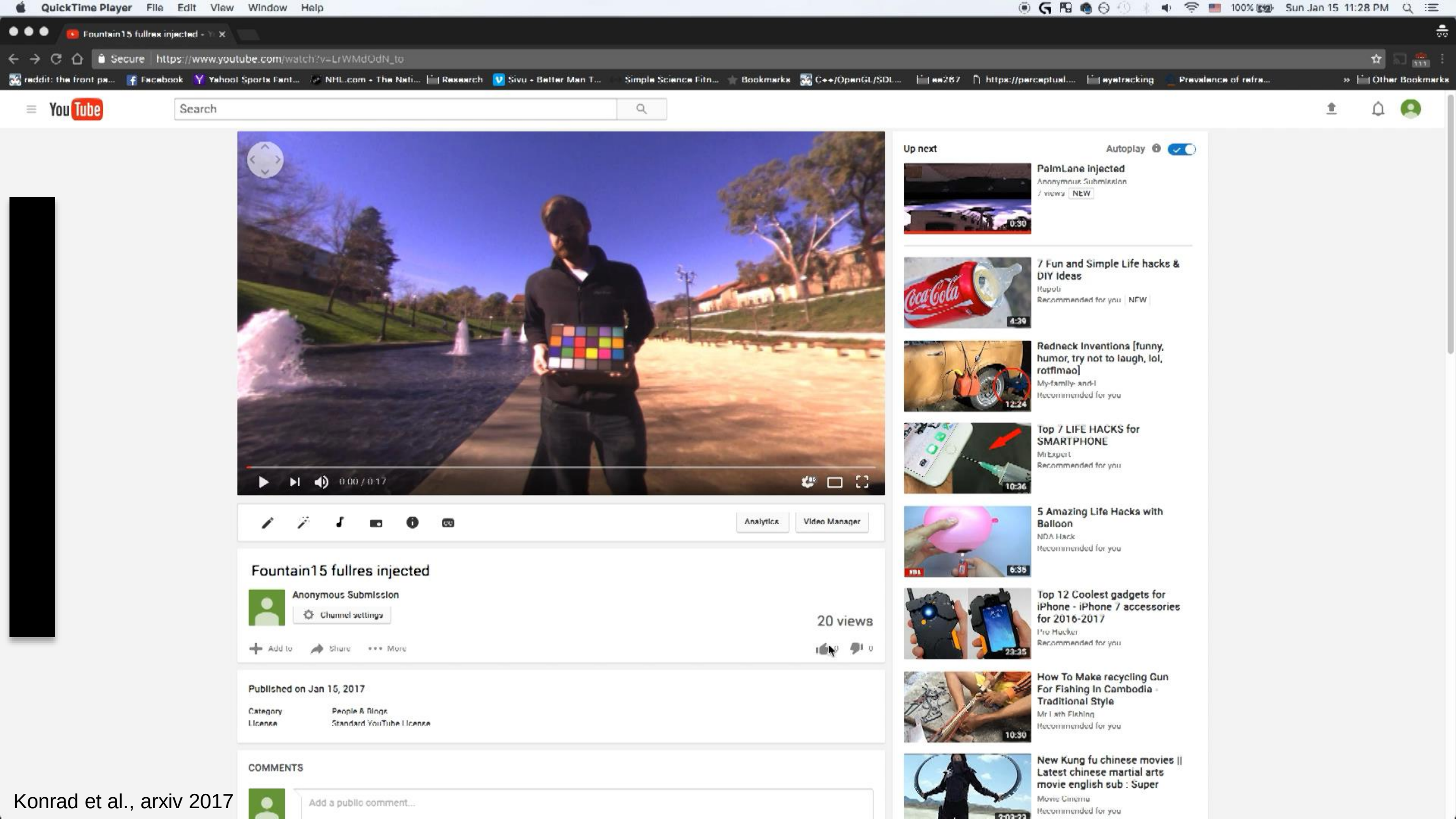


Konrad et al., arxiv 2017

Conclusions

Advancing AR/VR technology requires deep understanding of human vision, optics, signal processing, computation, and more.

Technology alone is not enough – engineer experiences!

Stanford EE 267

Stanford Computational Imaging Lab

Light Field Displays

Light Field Cameras

Computational Microscopy

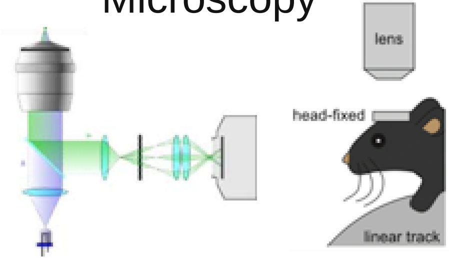
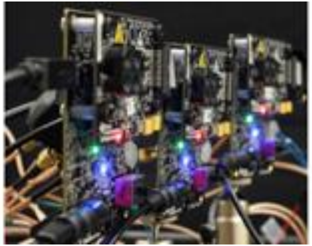
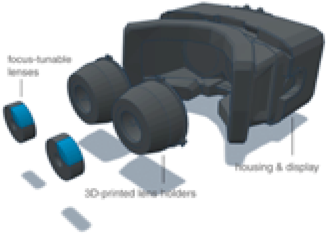


Image Optimization

Time-of-Flight Imaging



Near-eye Displays



Acknowledgements

<u>Near-eye Displays</u>

- Robert Konrad (Stanford)
- Nitish Padmanaban (Stanford)
- Fu-Chung Huang (NVIDIA)
- Emily Cooper (Dartmouth College)

<u>Spinning VR Camera</u>

- Robert Konrad (Stanford)
- Donald Dansereau (Stanford)

<u>Other</u>

- Wolfgang Heidrich (UBC/KAUST)
- Ramesh Raskar (MIT/Facebook)
- Douglas Lanman (Oculus)
- Matt Hirsch (Lumii)
- Matthew O'Toole (Stanford)
- Felix Heide (Stanford)

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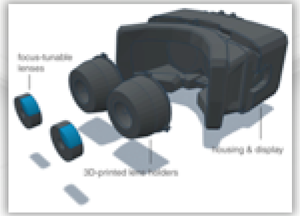
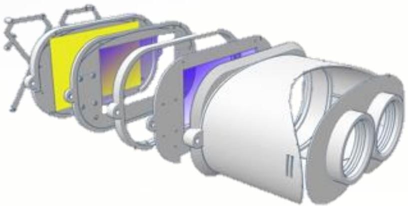
www.computationalimaging.org





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