HMD Display Optics II

Gordon Wetzstein
Stanford University

EE 267 Virtual Reality

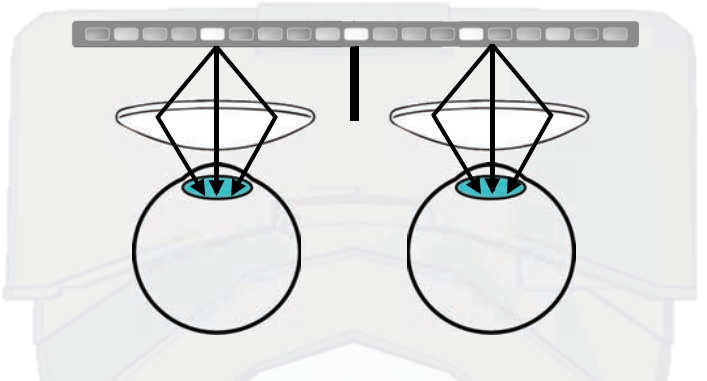
Lecture 8

stanford.edu/class/ee267/

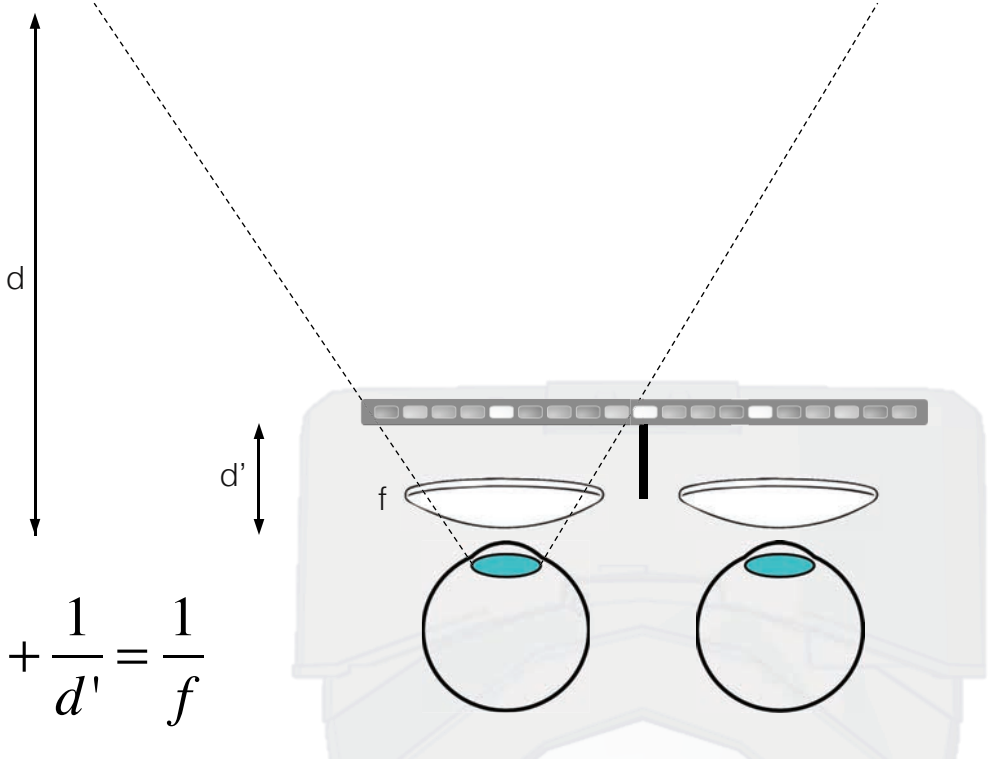
Lecture Overview

- focus cues & the vergence-accommodation conflict
- advanced optics for VR with focus cues:
  - adaptive and gaze-contingent focus displays
  - monovision
  - volumetric and multi-plane displays
  - near-eye light field displays
  - Maxwellian-type displays

- AR displays
- microdisplays used for VR/AR



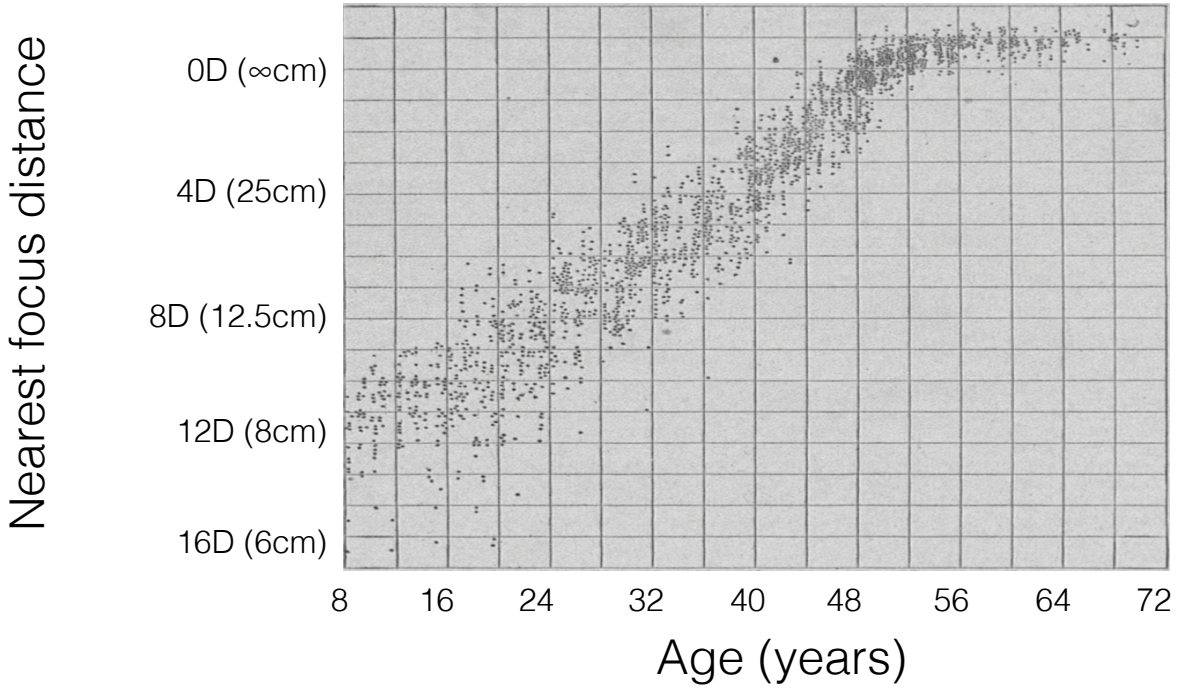
Magnified Display



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

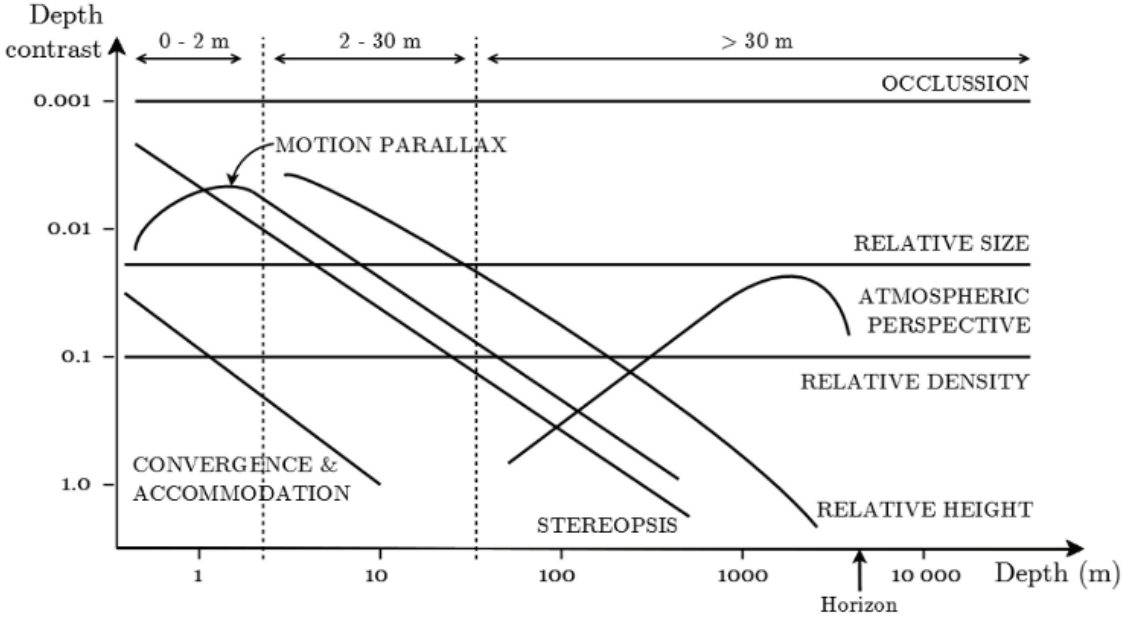
- big challenge: virtual image appears at fixed focal plane!
- no focus cues

Importance of Focus Cues Decreases with Age - Presbyopia



Duane, 1912

Relative Importance of Depth Cues



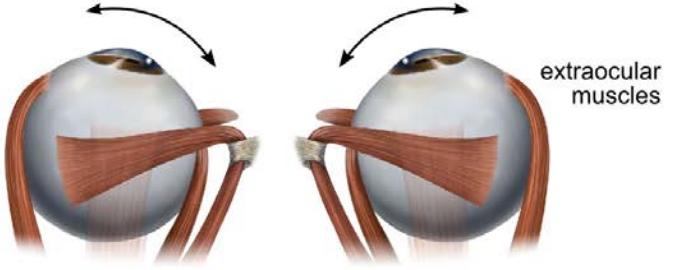
Cutting & Vishton, 1995

The Vergence-Accommodation Conflict (VAC)

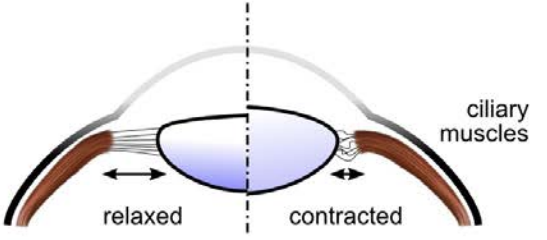
Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue



Vergence

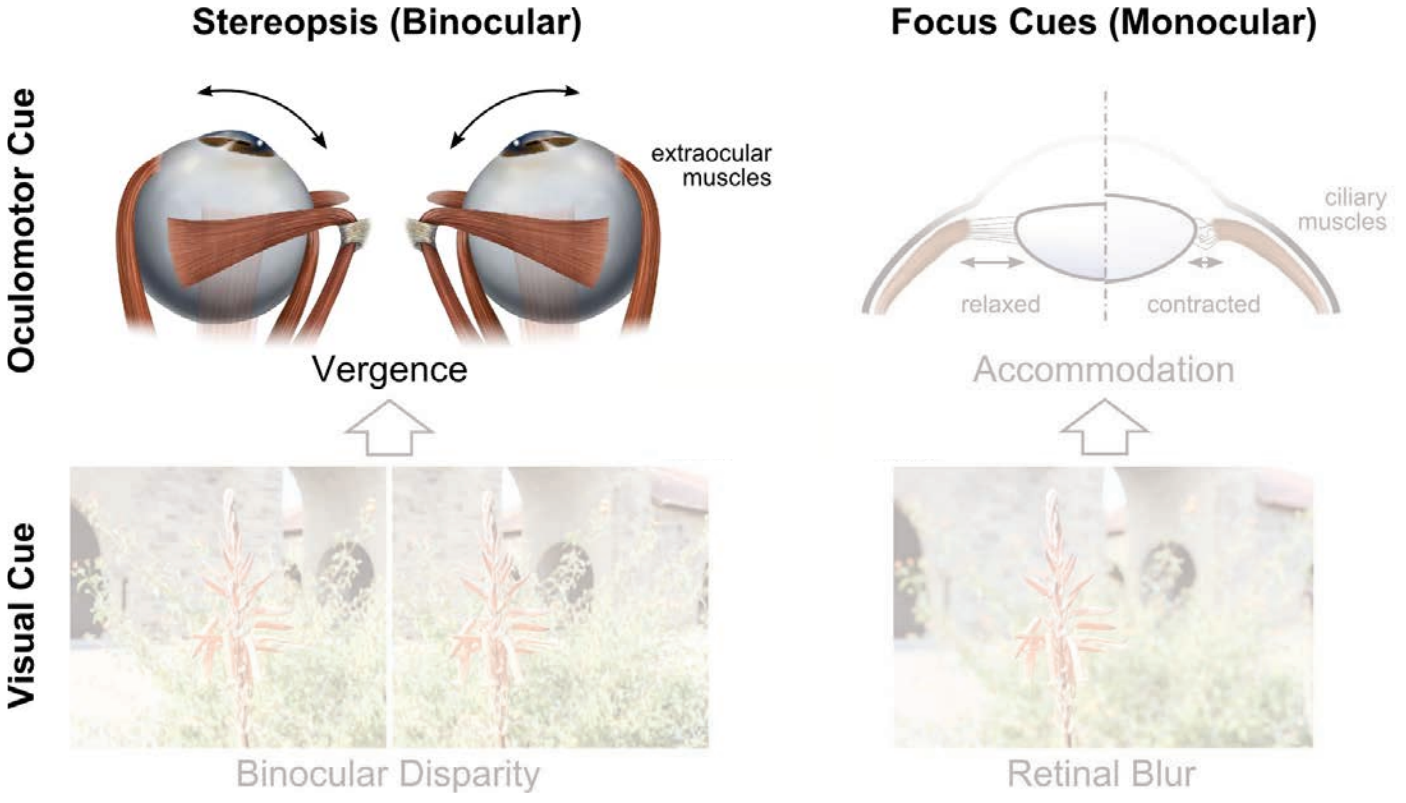


Accommodation

Visual Cue

Binocular Disparity

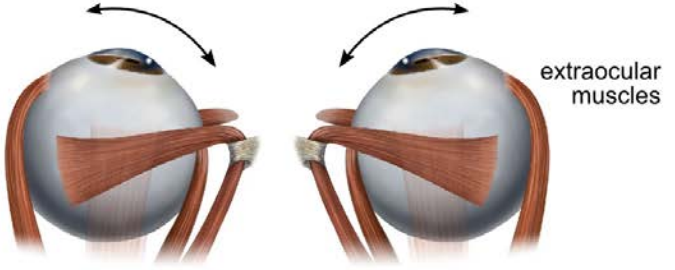
Retinal Blur


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

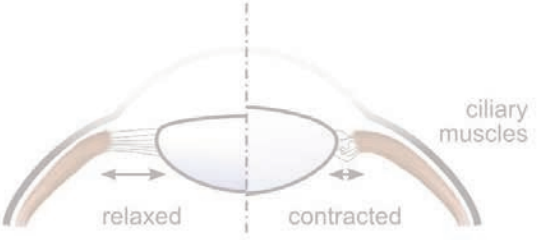
Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue



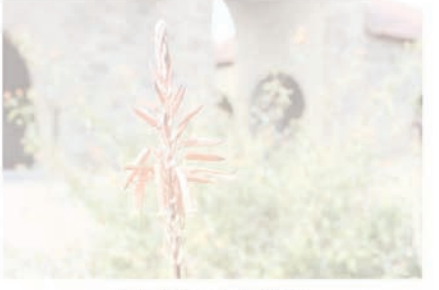
Vergence



Accommodation

Visual Cue

Binocular Disparity

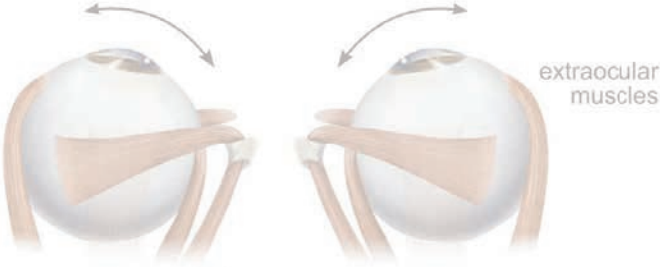


Retinal Blur

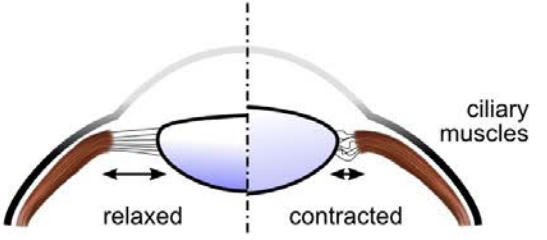
Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue



Vergence



Accommodation

Visual Cue

Binocular Disparity

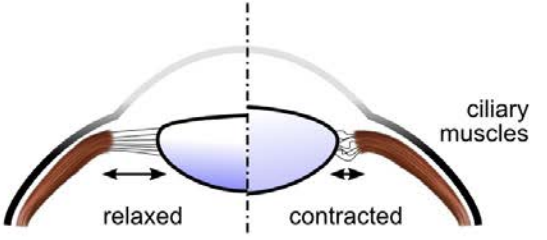
Retinal Blur

Stereopsis (Binocular)

Focus Cues (Monocular)

Oculomotor Cue

Vergence

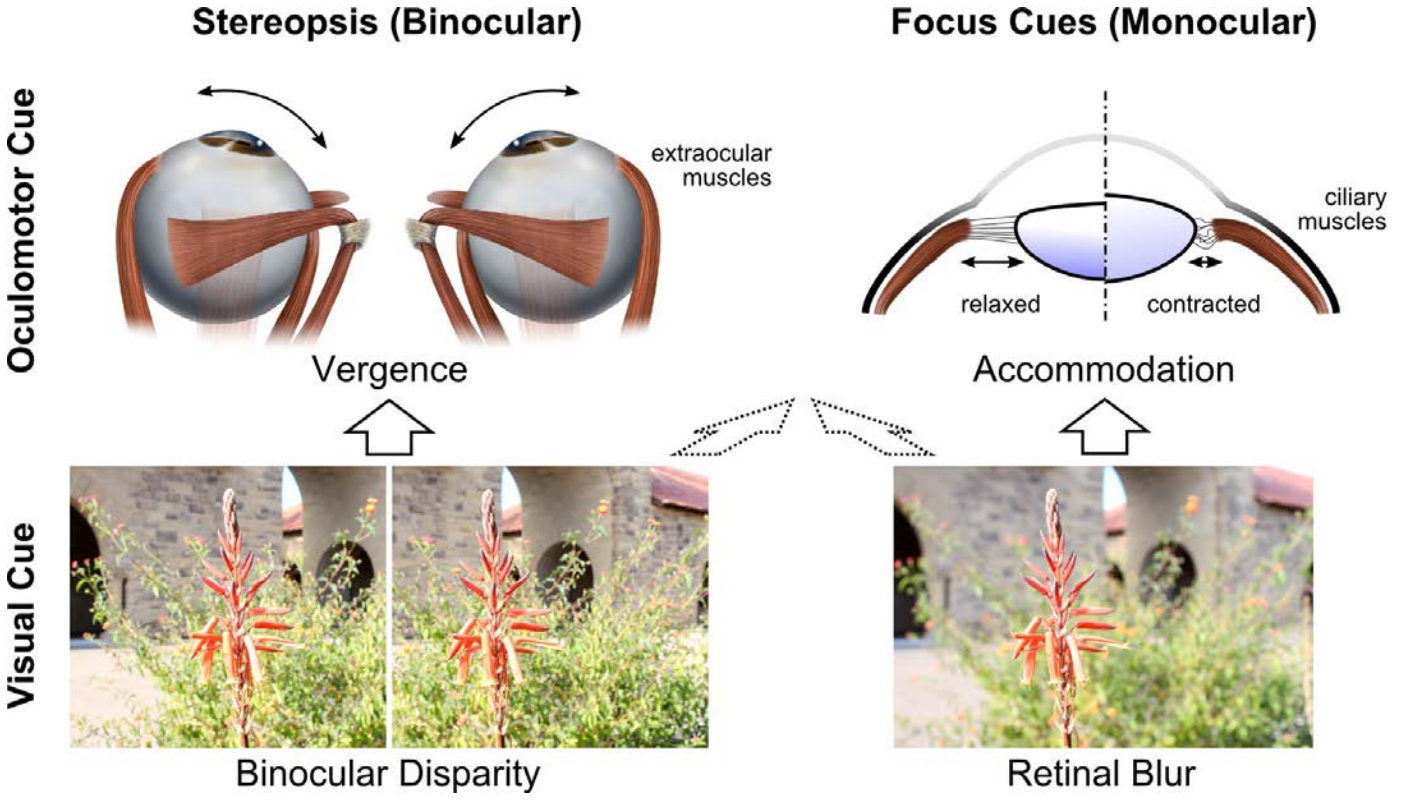


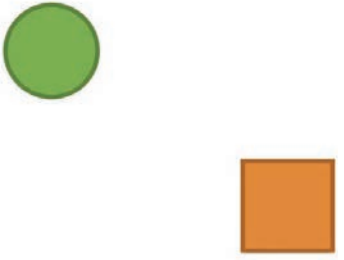
Accommodation

Visual Cue

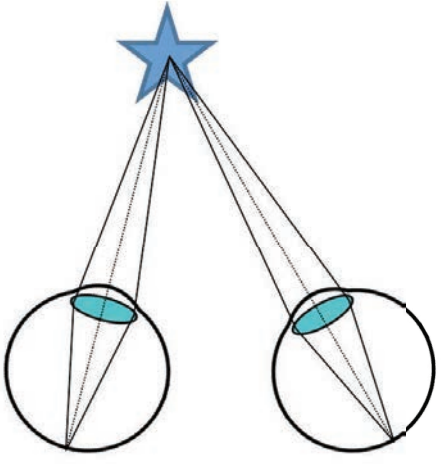
Binocular Disparity

Retinal Blur

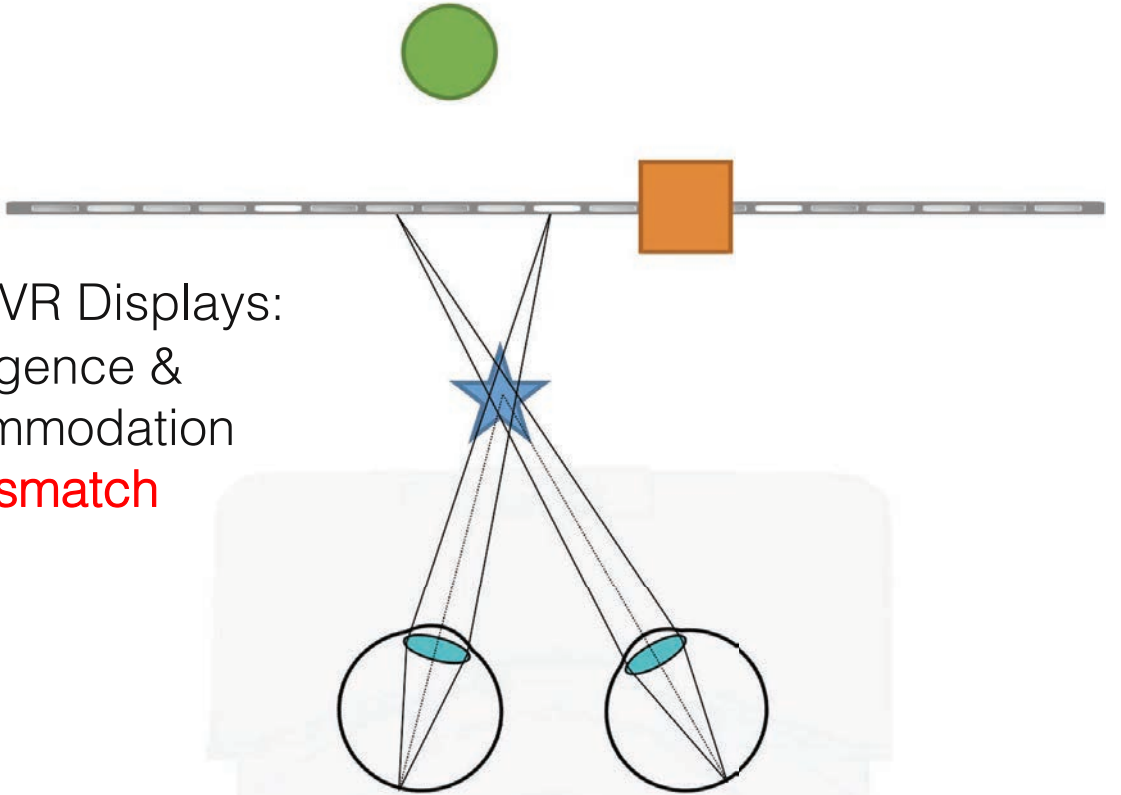

Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
ciliary muscles
relaxed
contracted
Vergence
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur



Real World:
Vergence &
Accommodation
Match!

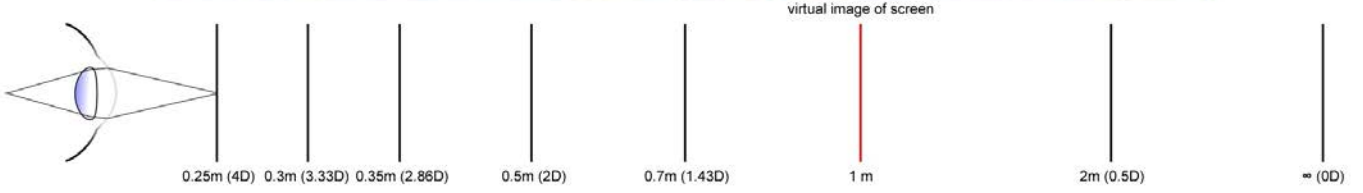


Current VR Displays:
Vergence &
Accommodation
Mismatch



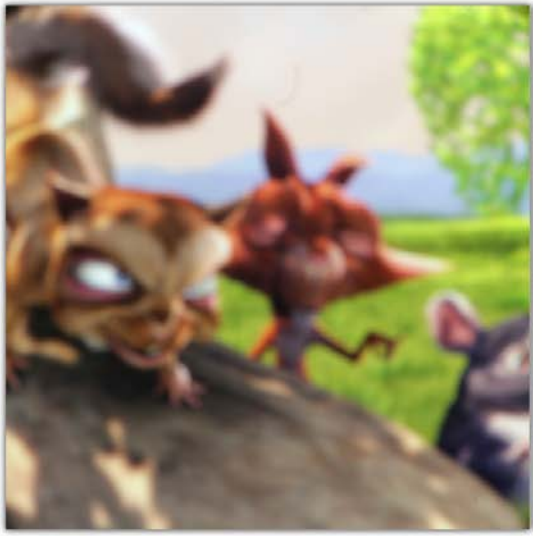
Accommodation and Retinal Blur

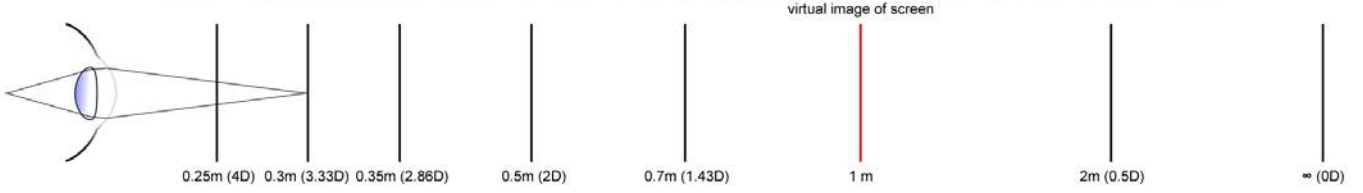
Conventional Display



Blur Gradient Driven Accommodation

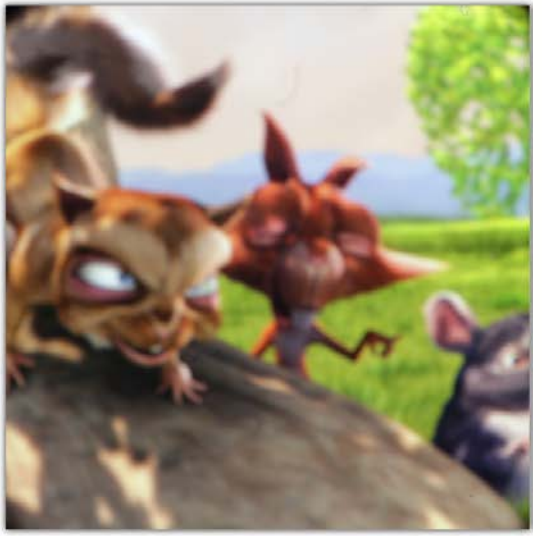
Conventional Display

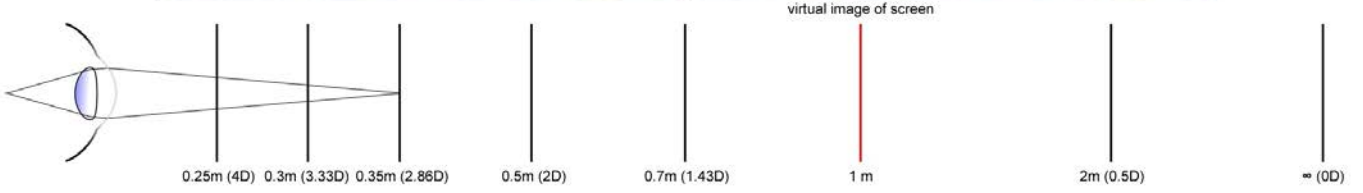




Blur Gradient Driven Accommodation

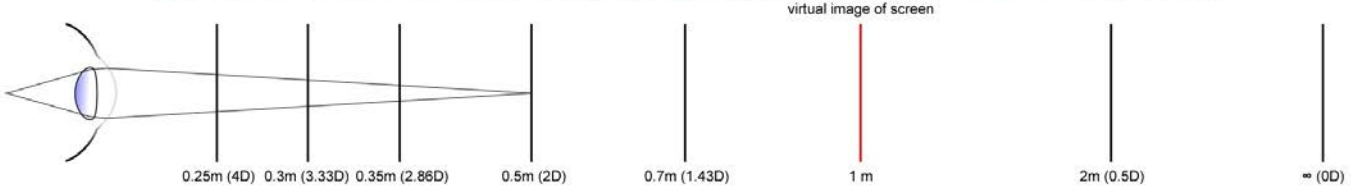
Conventional Display





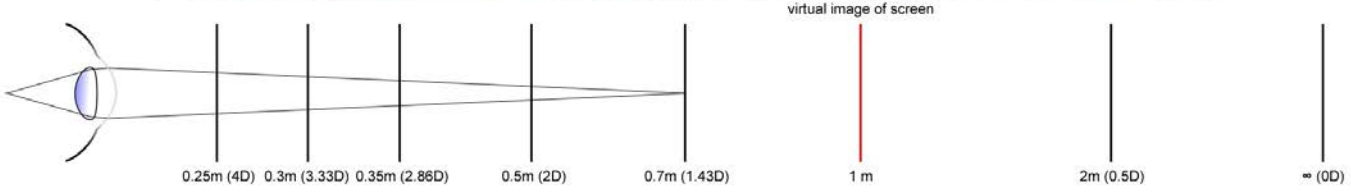
Blur Gradient Driven Accommodation

Conventional Display



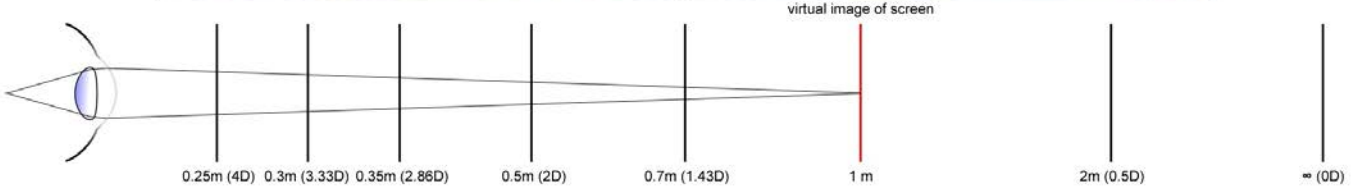
Blur Gradient Driven Accommodation

Conventional Display

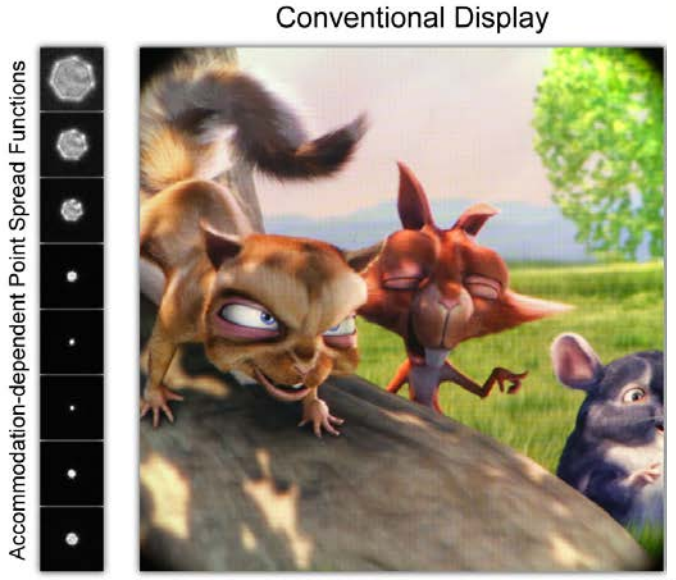


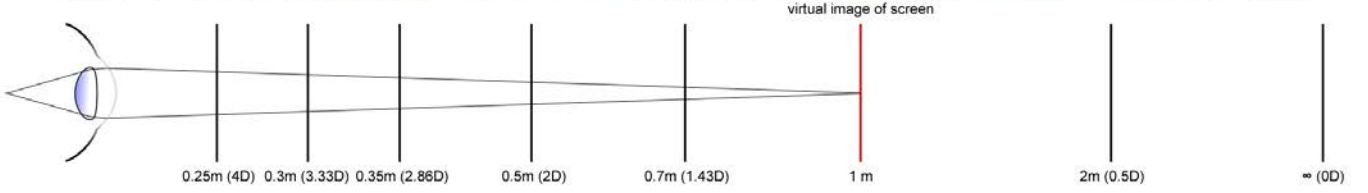
Blur Gradient Driven Accommodation

Conventional Display



Blur Gradient Driven Accommodation

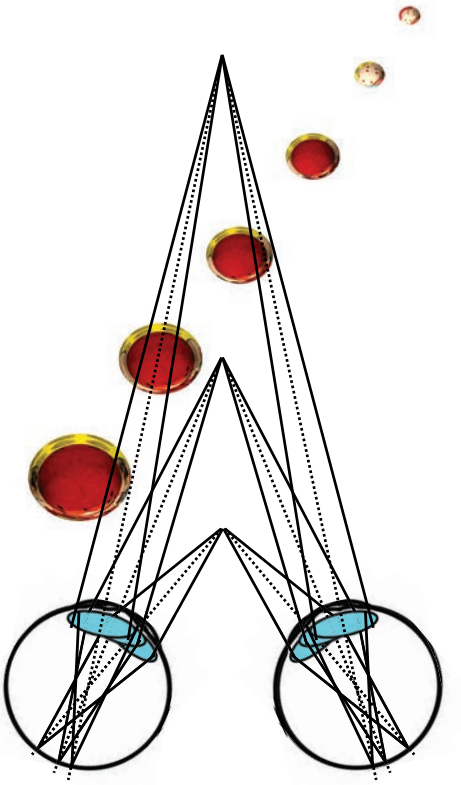


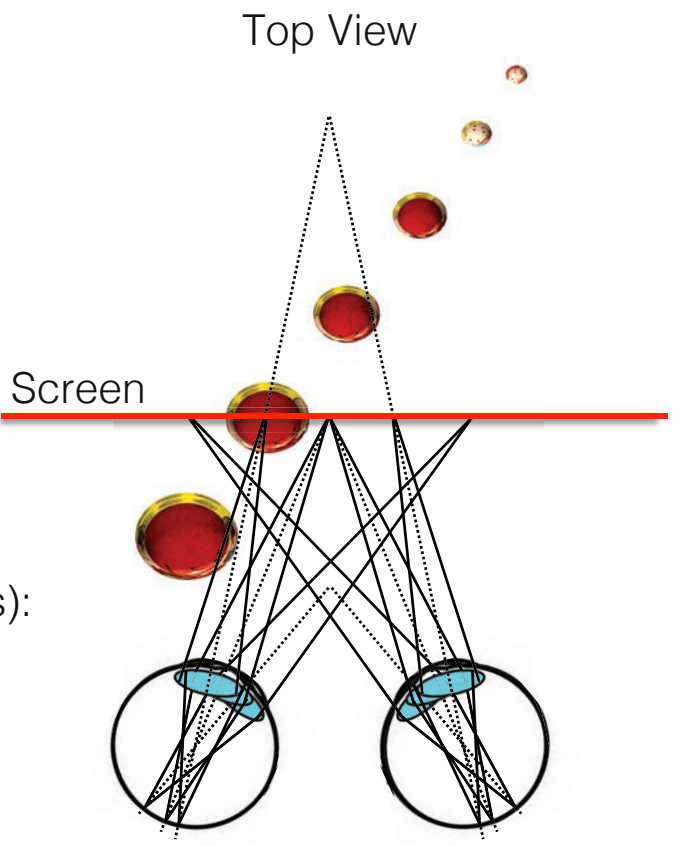


Real World:

Vergence & Accommodation Match!

Top View





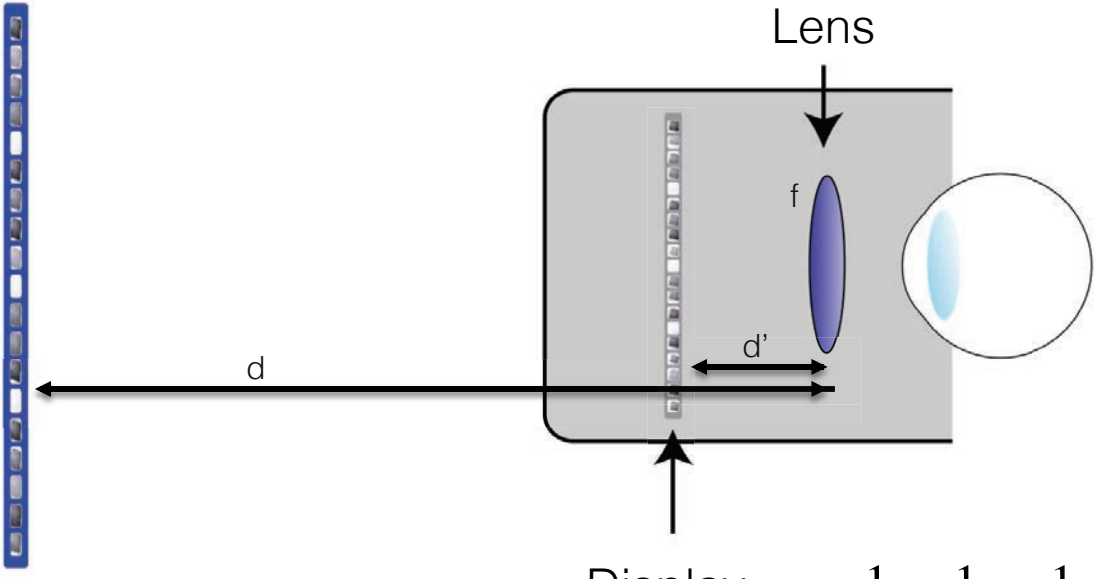
Stereo Displays Today (including HMDs):

Vergence-Accommodation Mismatch!

VR Displays with Focus Cues

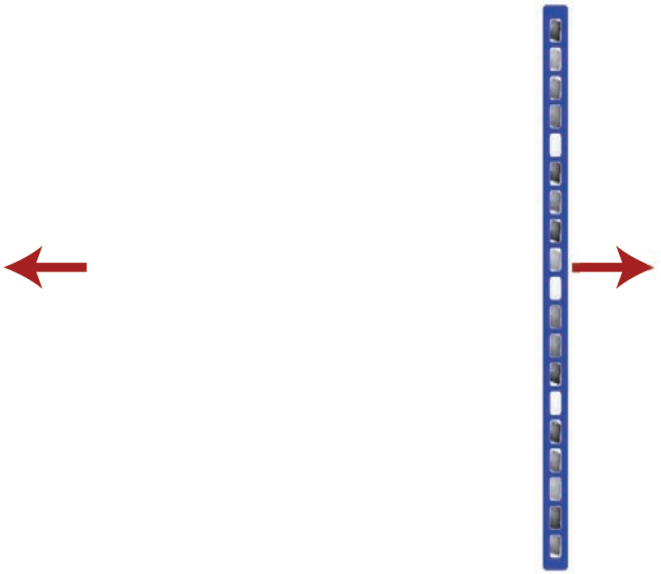
1. Adaptive and Gaze-contingent Focus

Fixed Focus



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

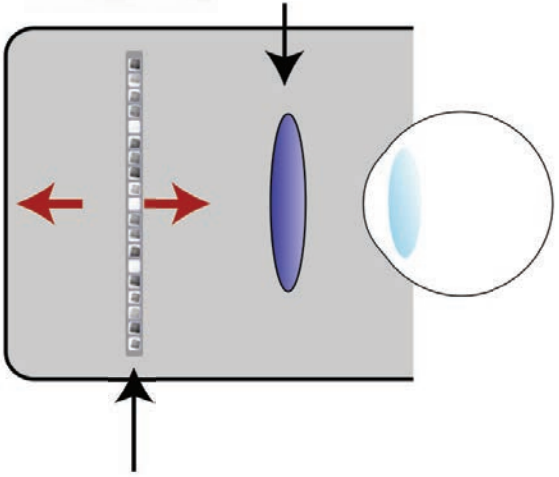
Adaptive Focus



Magnified Display

actuator → vary d'

Lens



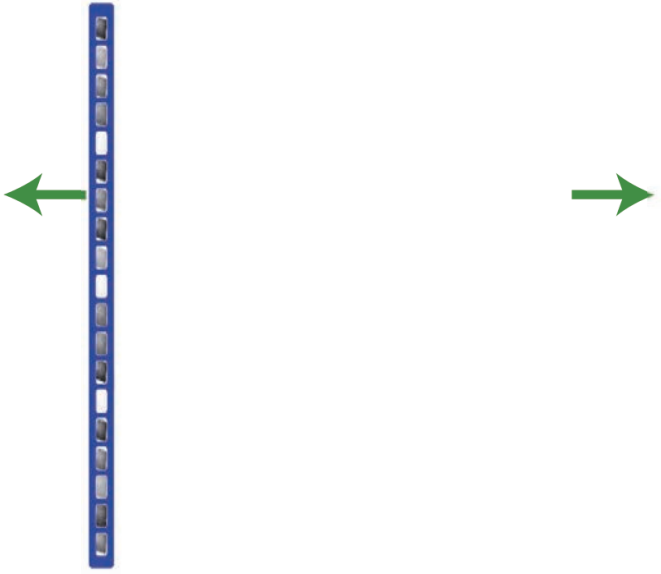
Display

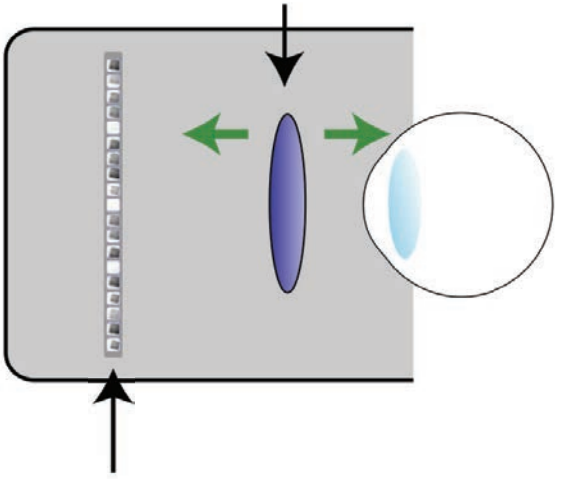
$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{f}$$

Adaptive Focus

focus-tunable lens → vary f

Lens



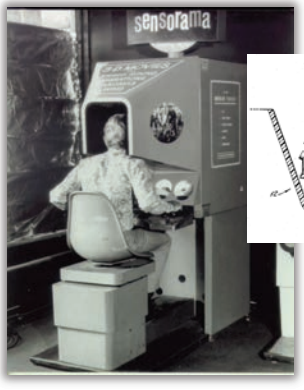


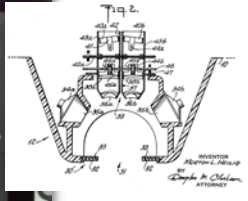
Display

Magnified Display

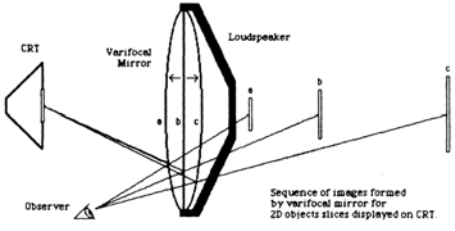
$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{f}$$

Adaptive Focus - History

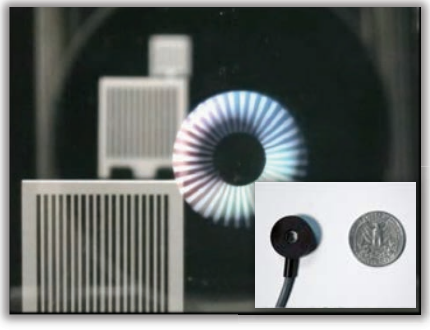




manual focus adjustment
Heilig 1962

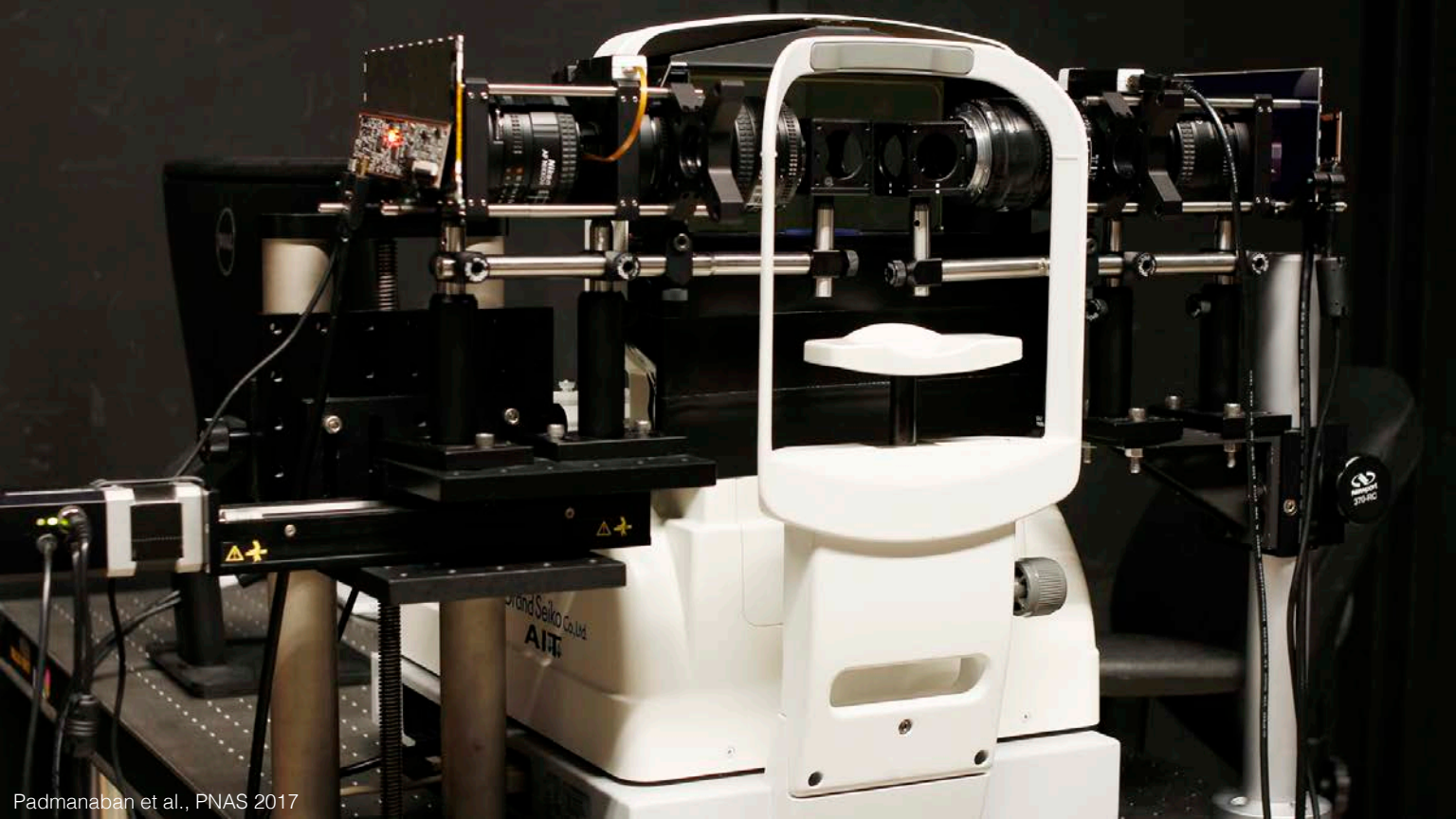


automatic focus adjustment
Mills 1984

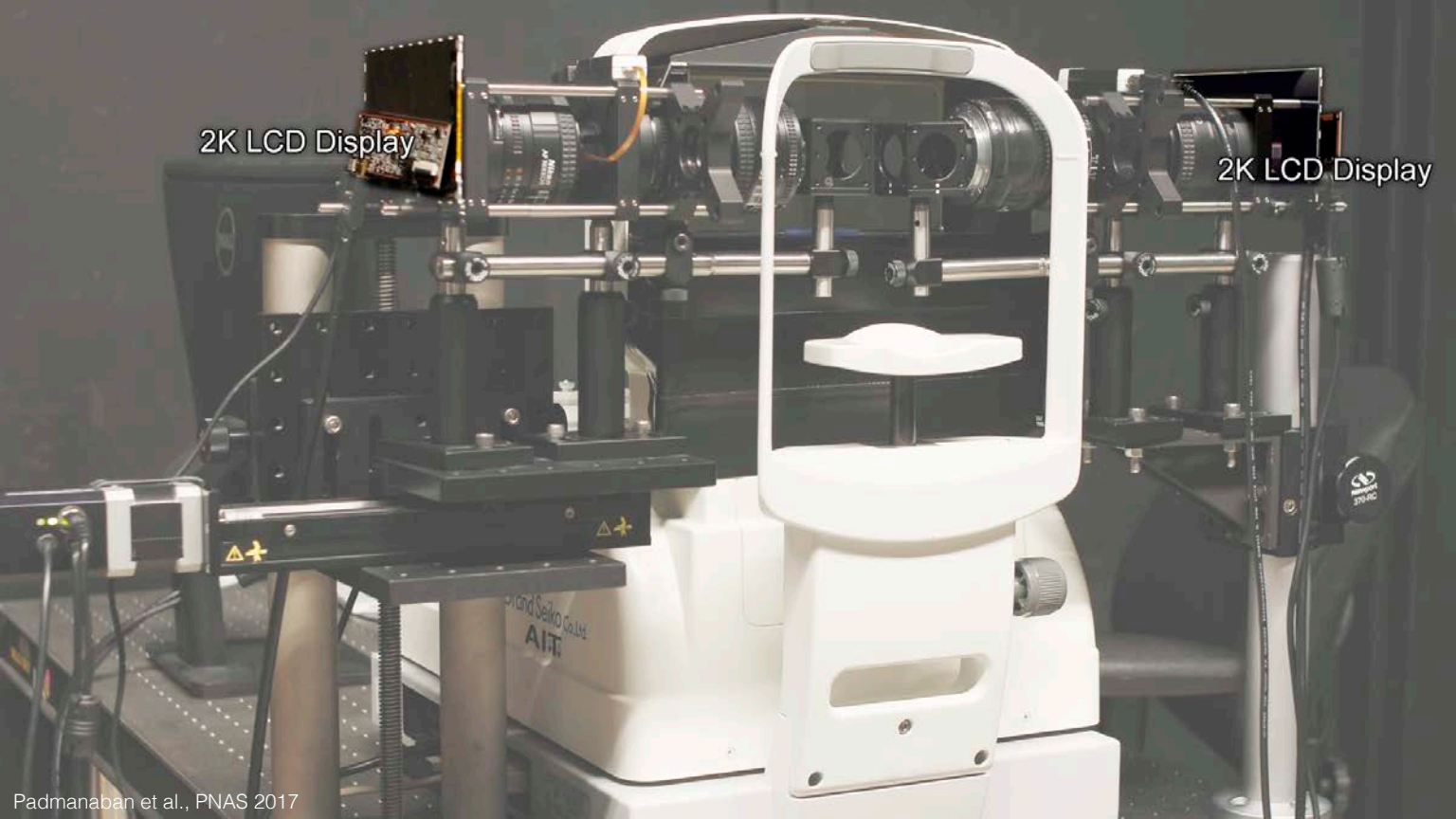


deformabe mirrors & lenses
McQuaide 2003, Liu 2008

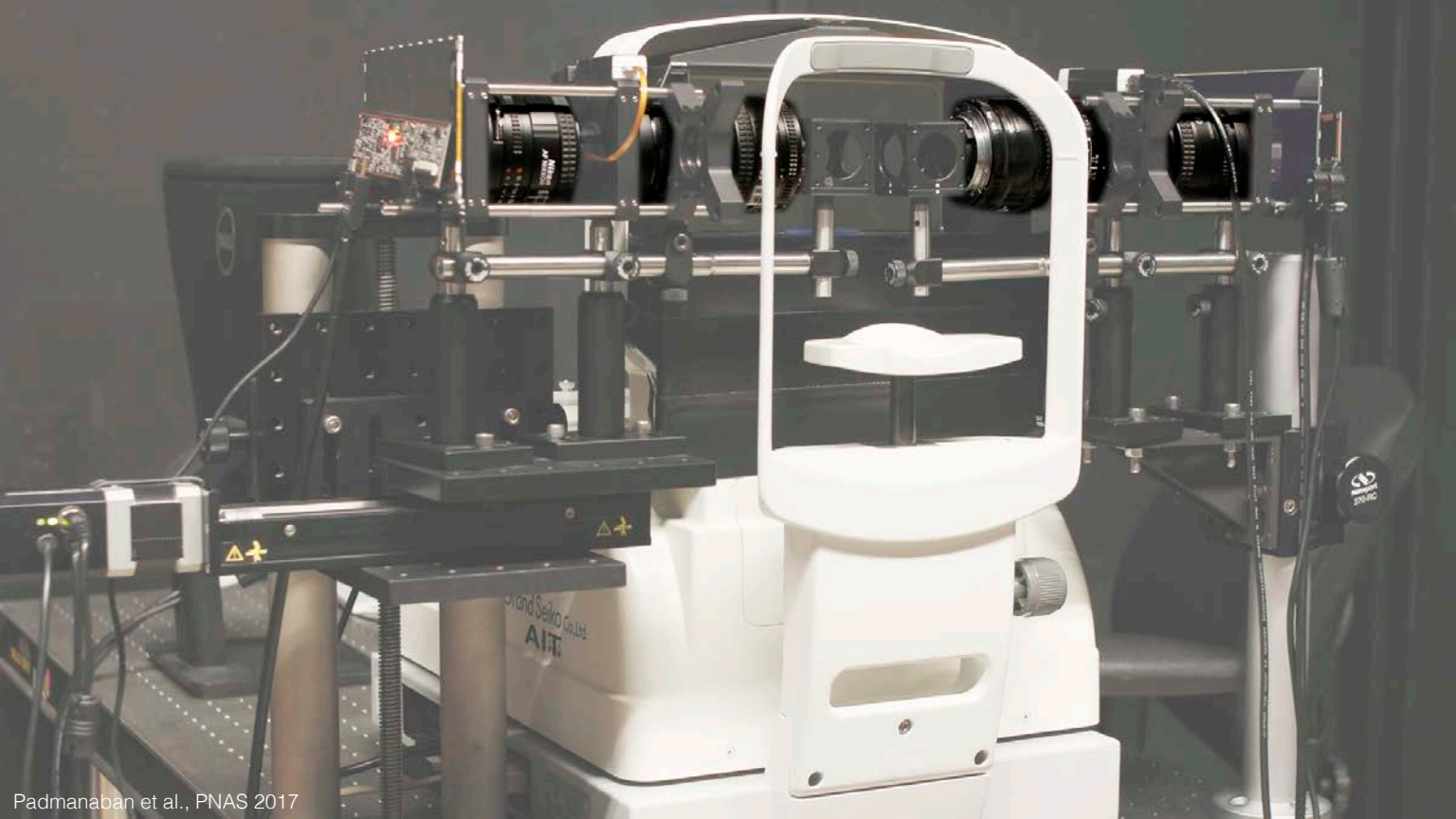
- M. Heilig “Sensorama”, 1962 (US Patent #3,050,870)
- P. Mills, H. Fuchs, S. Pizer “High-Speed Interaction On A Vibrating-Mirror 3D Display”, SPIE 0507 1984
- S. Shiwa, K. Omura, F. Kishino “Proposal for a 3-D display with accommodative compensation: 3DDAC”, JSID 1996
- S. McQuaide, E. Seibel, J. Kelly, 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



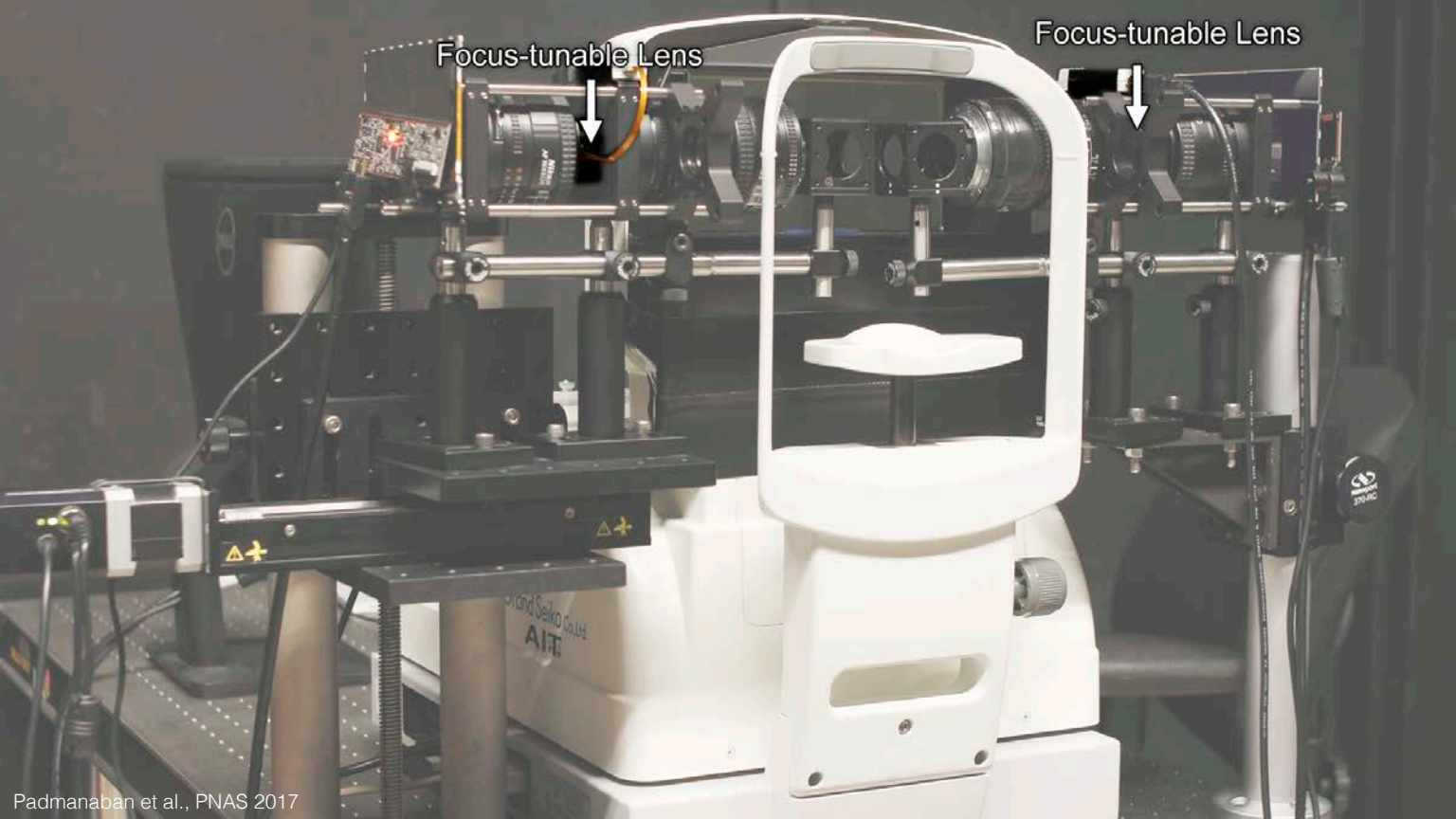
Padmanaban et al., PNAS 2017



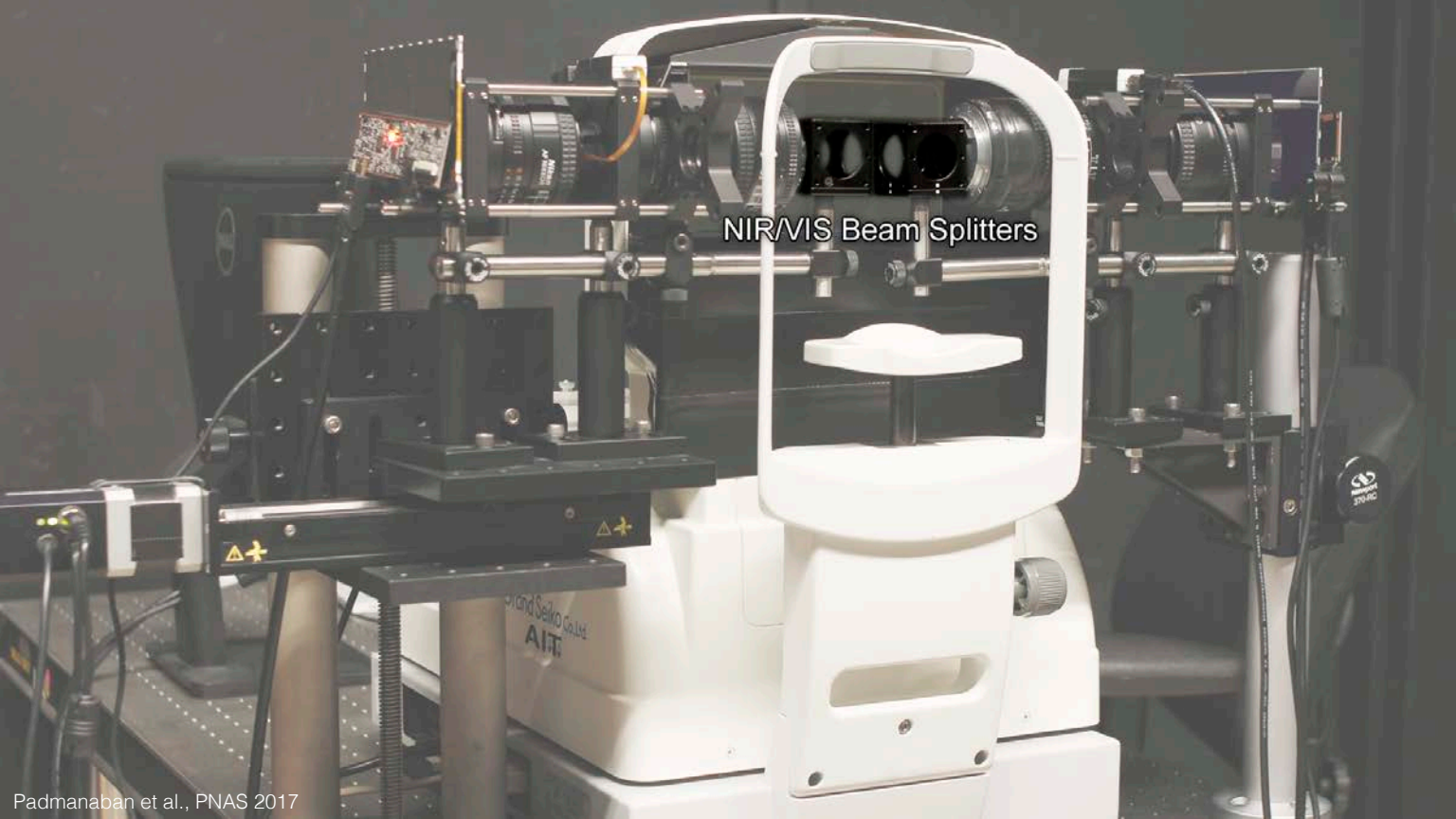
Padmanaban et al., PNAS 2017



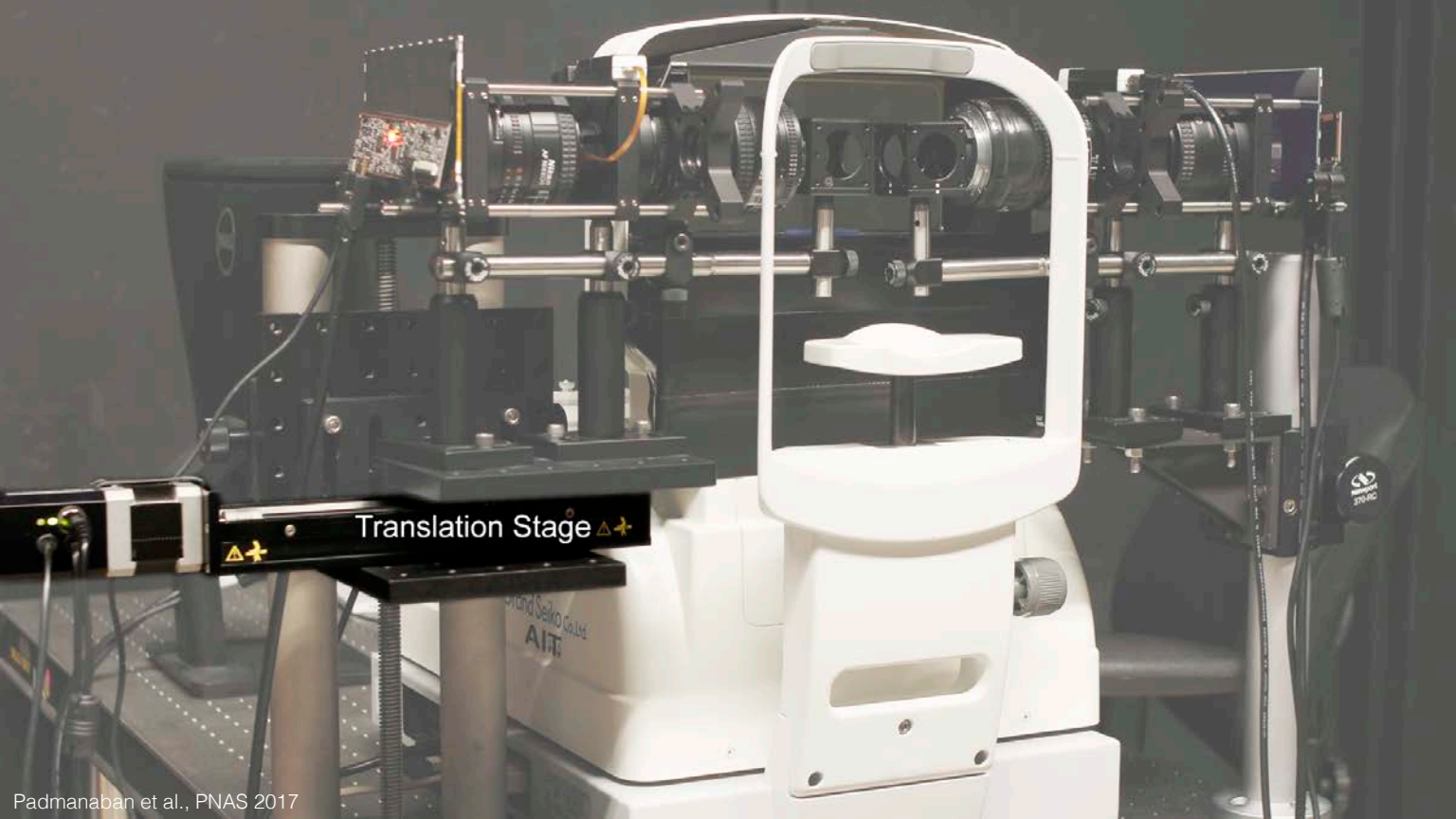
Padmanaban et al., PNAS 2017



Padmanaban et al., PNAS 2017

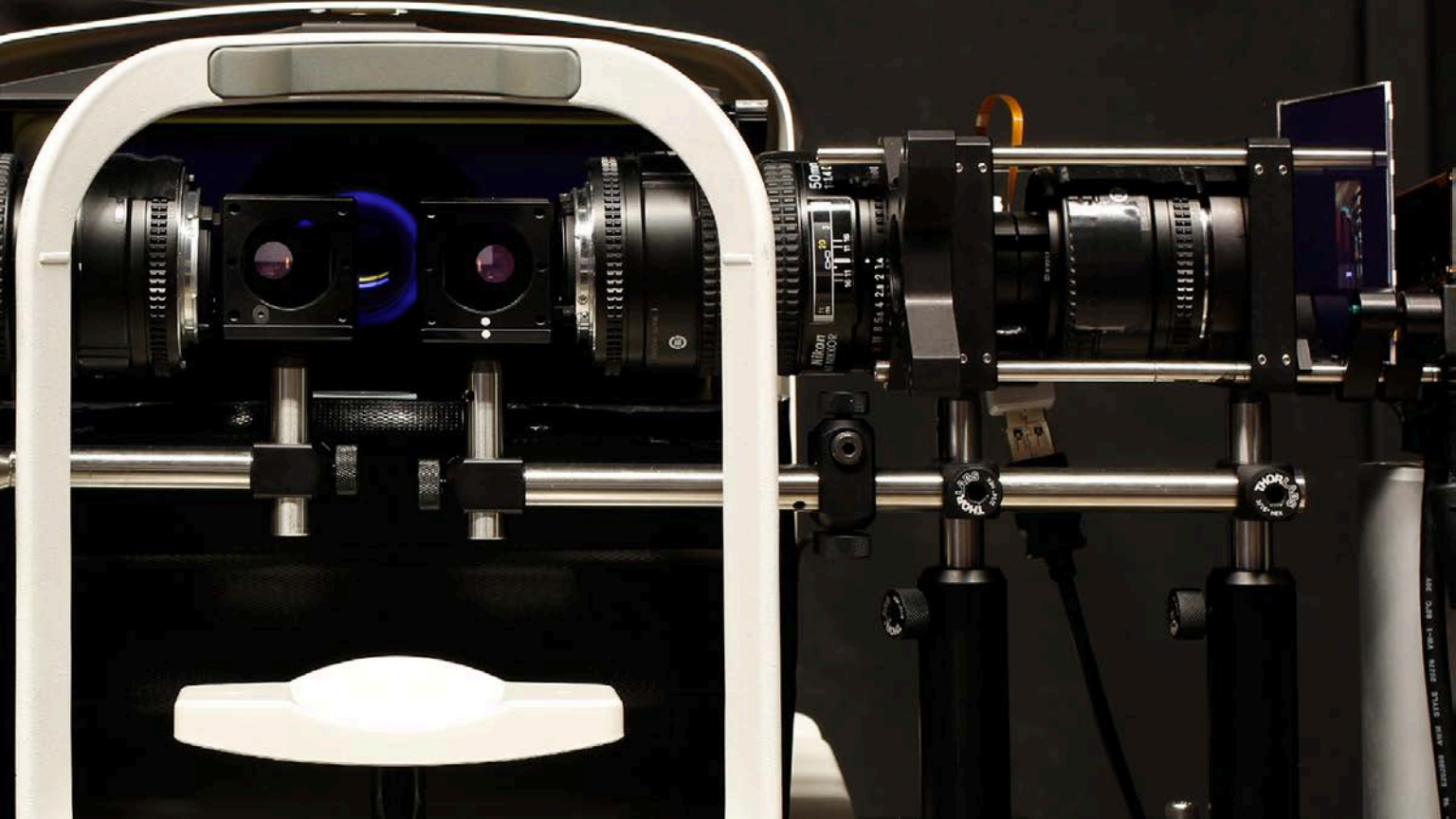


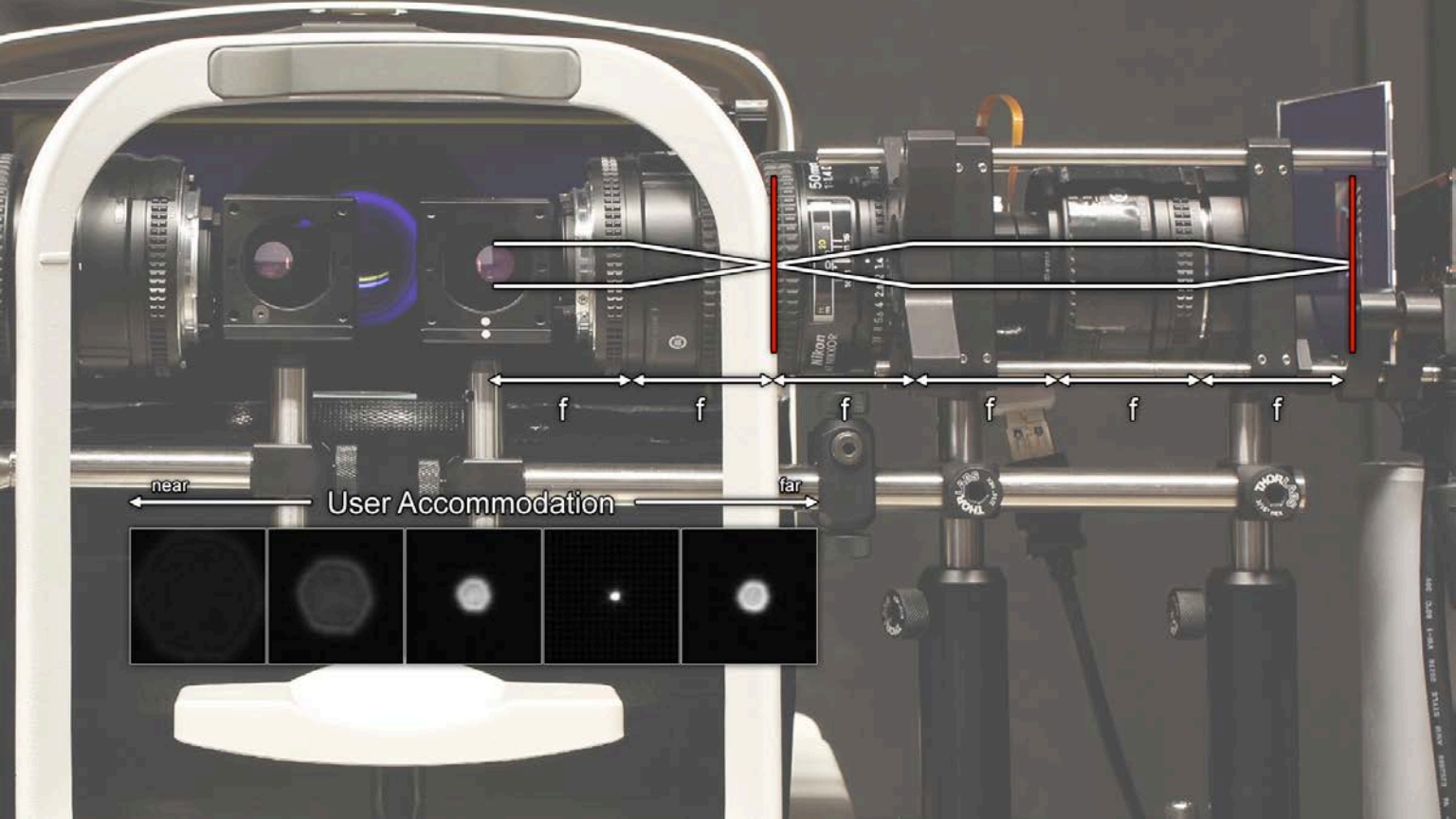
Padmanaban et al., PNAS 2017

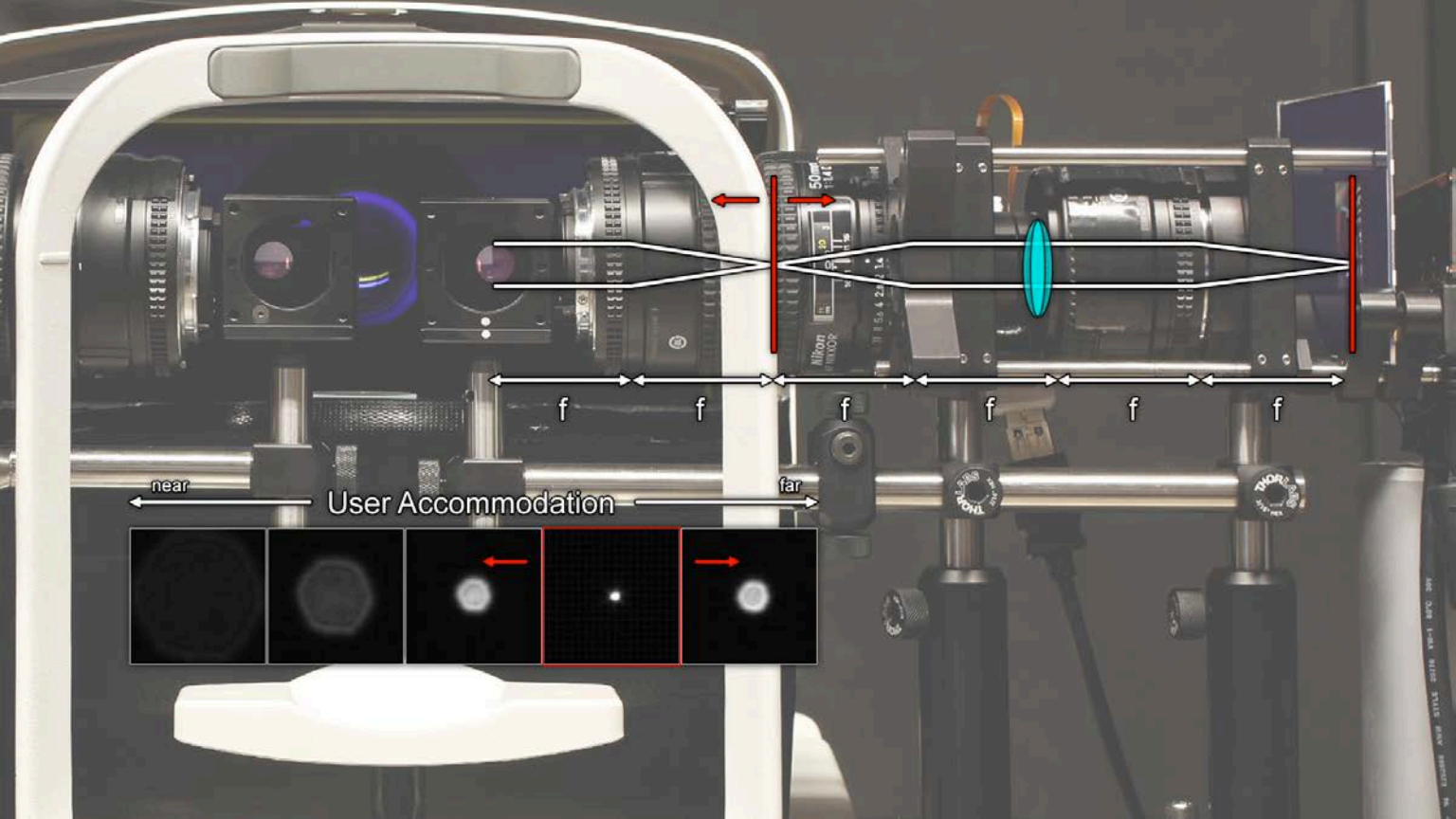


Padmanaban et al., PNAS 2017

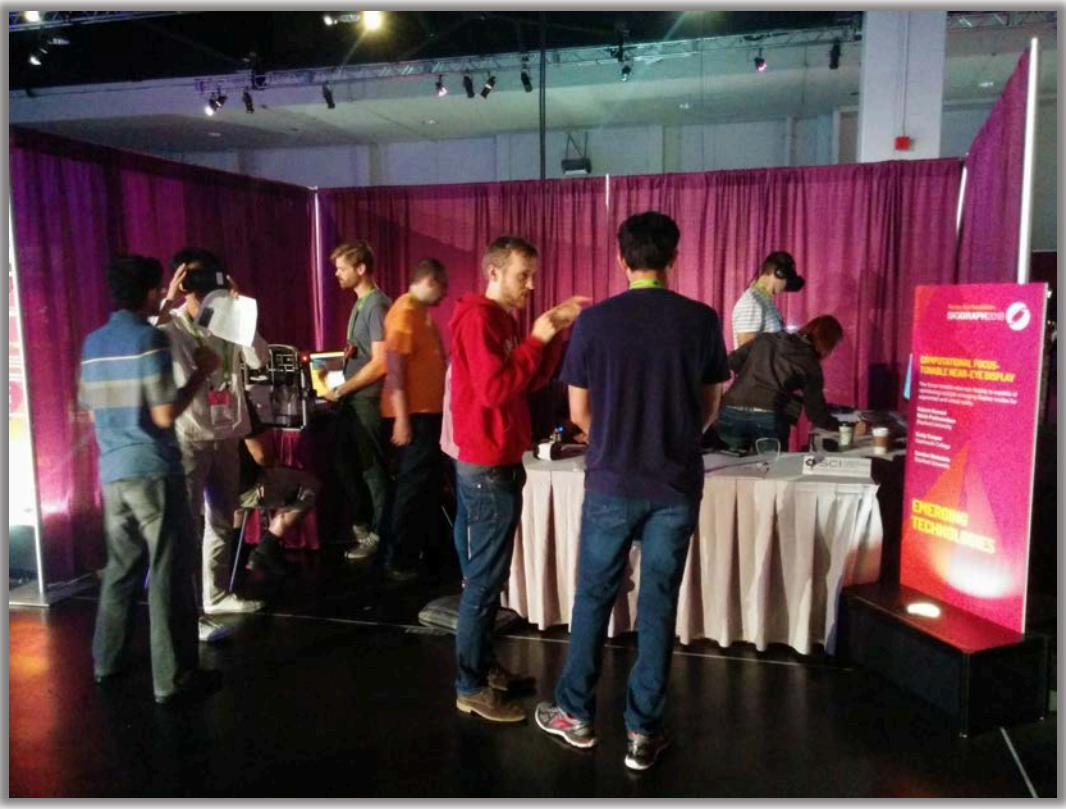
Padmanaban et al., PNAS 2017


50mm
Nikon
THORLABS


f
f
f
f
f
f
near
User Accommodation
far


f
f
f
f
f
f
near
User Accommodation
far

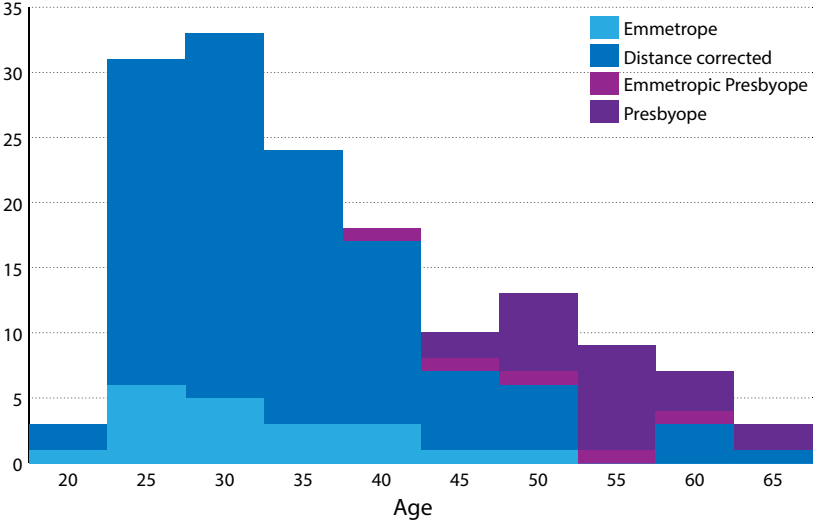
EyeNetra.com



at ACM SIGGRAPH 2016

EyeNetra.com

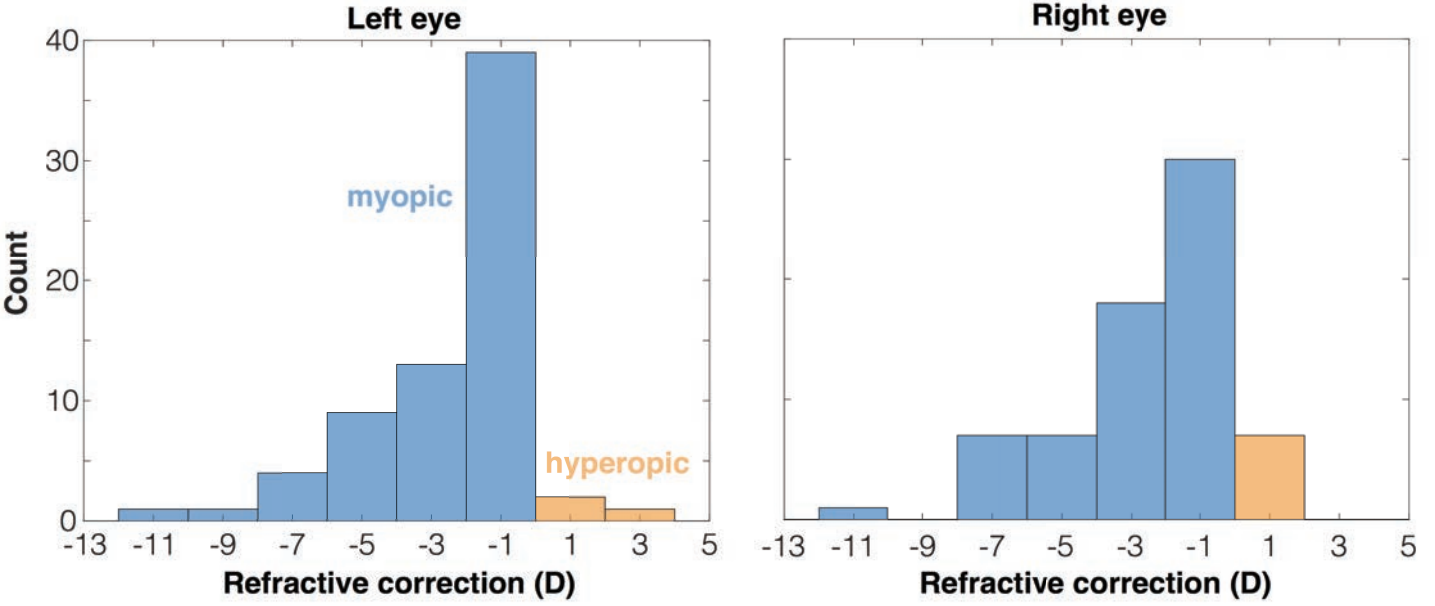
participants of the study, 152 total



at ACM SIGGRAPH 2016

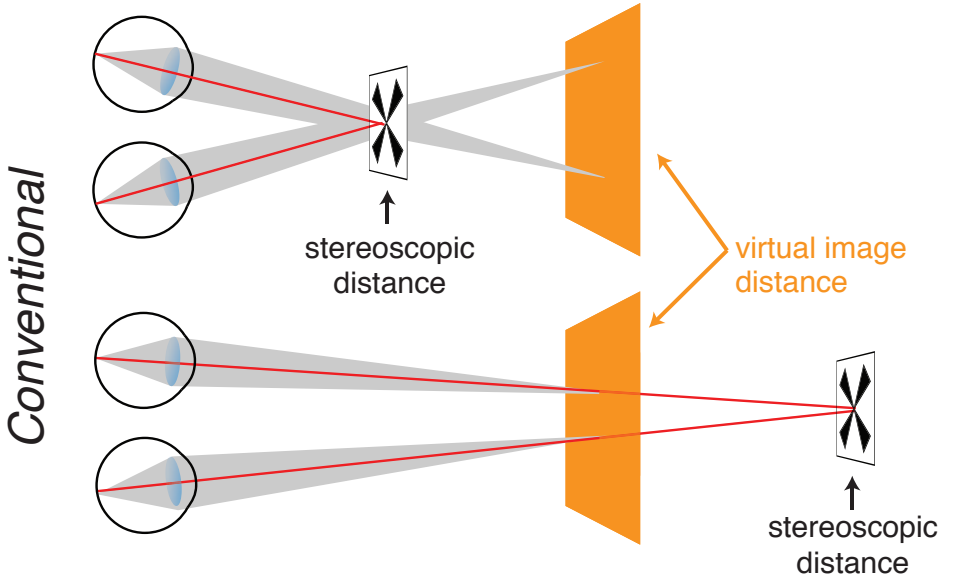
Participants - Prescription

n = 70, ages 21-64



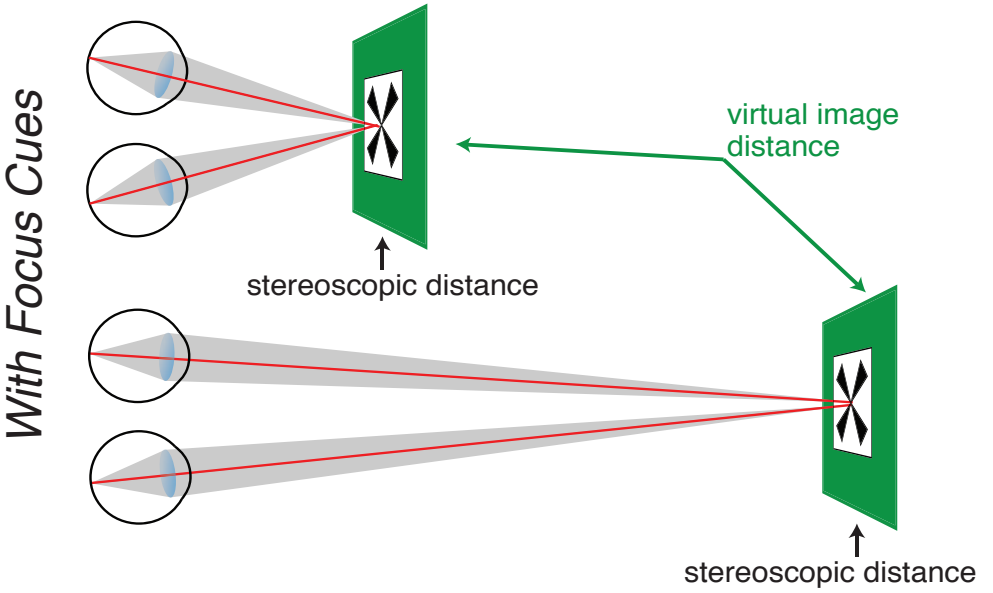
Padmanaban et al., PNAS 2017

Conventional Stereo / VR Display



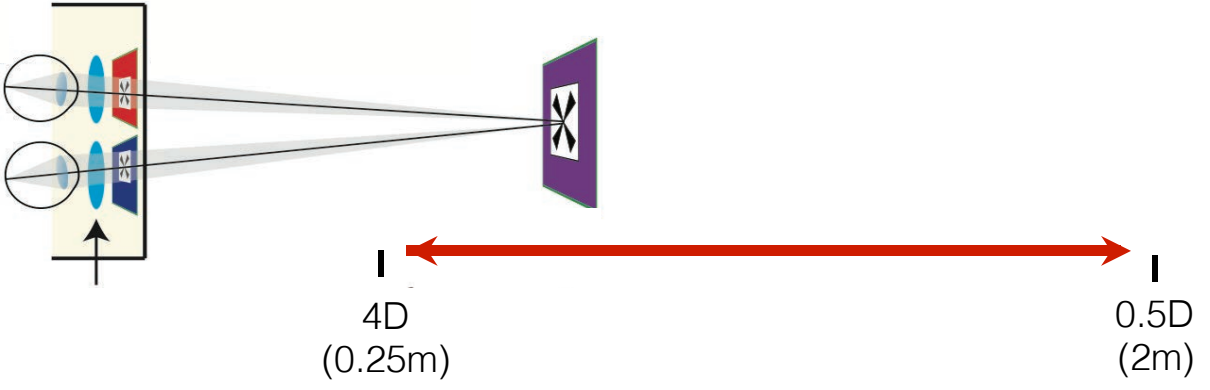
vergence
accommodation

Removing VAC with Adaptive Focus



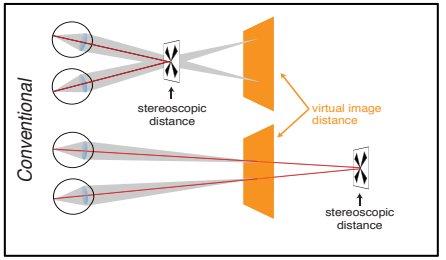
vergence
accommodation

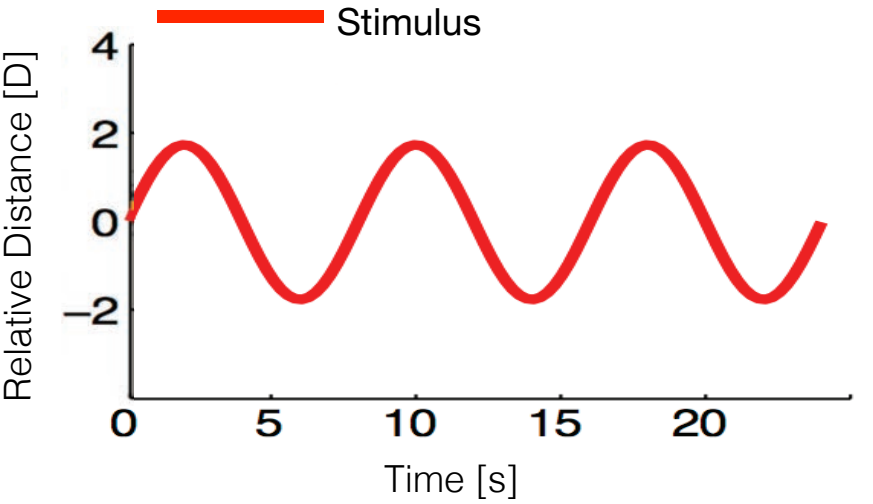
Task



Follow the target with your eyes

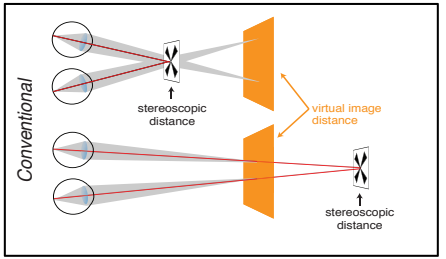
Accommodative Response

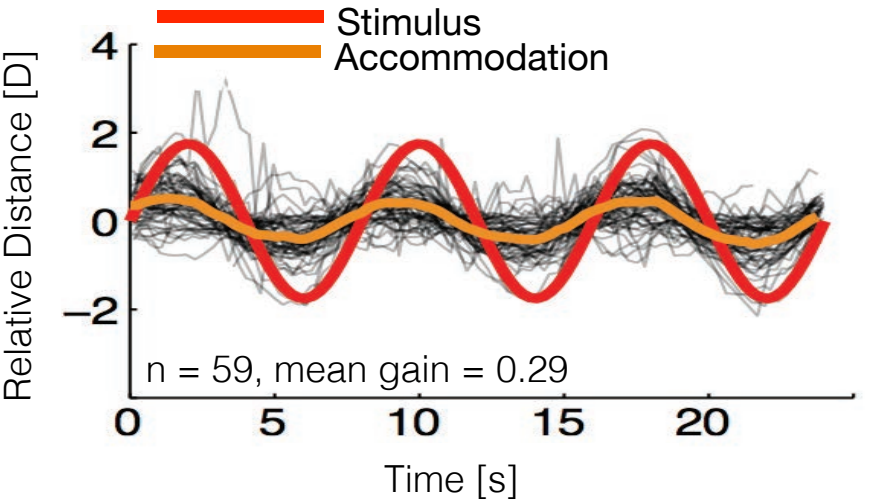




Padmanaban et al., PNAS 2017

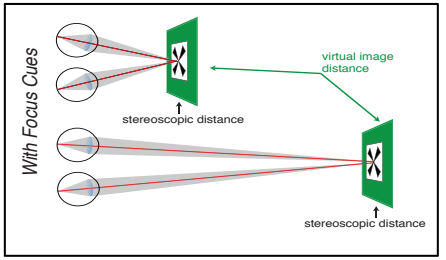
Accommodative Response

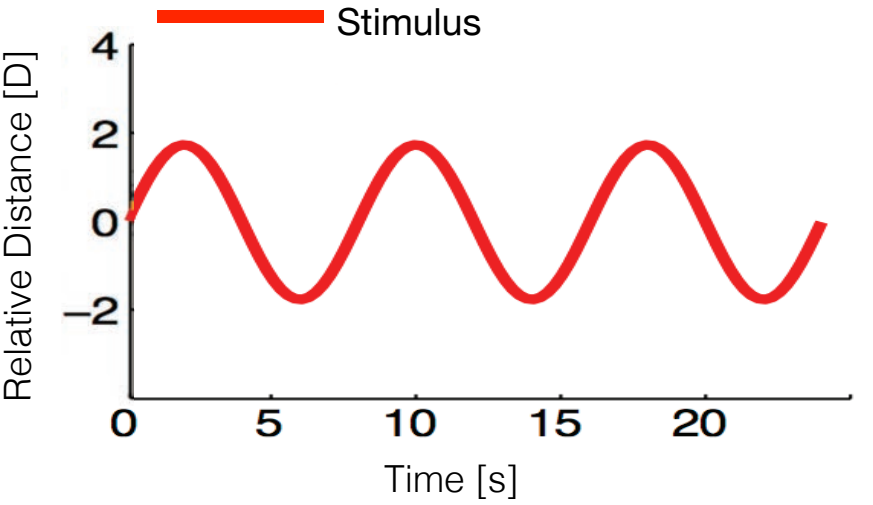




Padmanaban et al., PNAS 2017

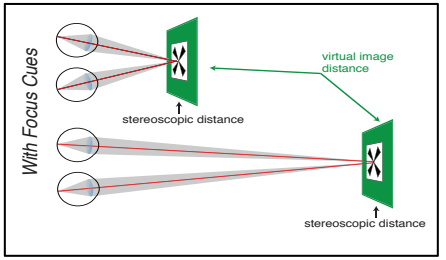
Accommodative Response

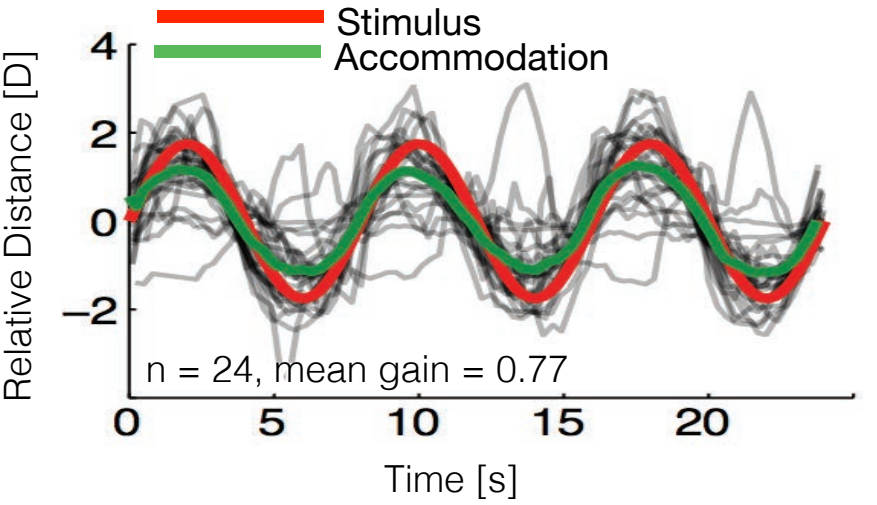




Padmanaban et al., PNAS 2017

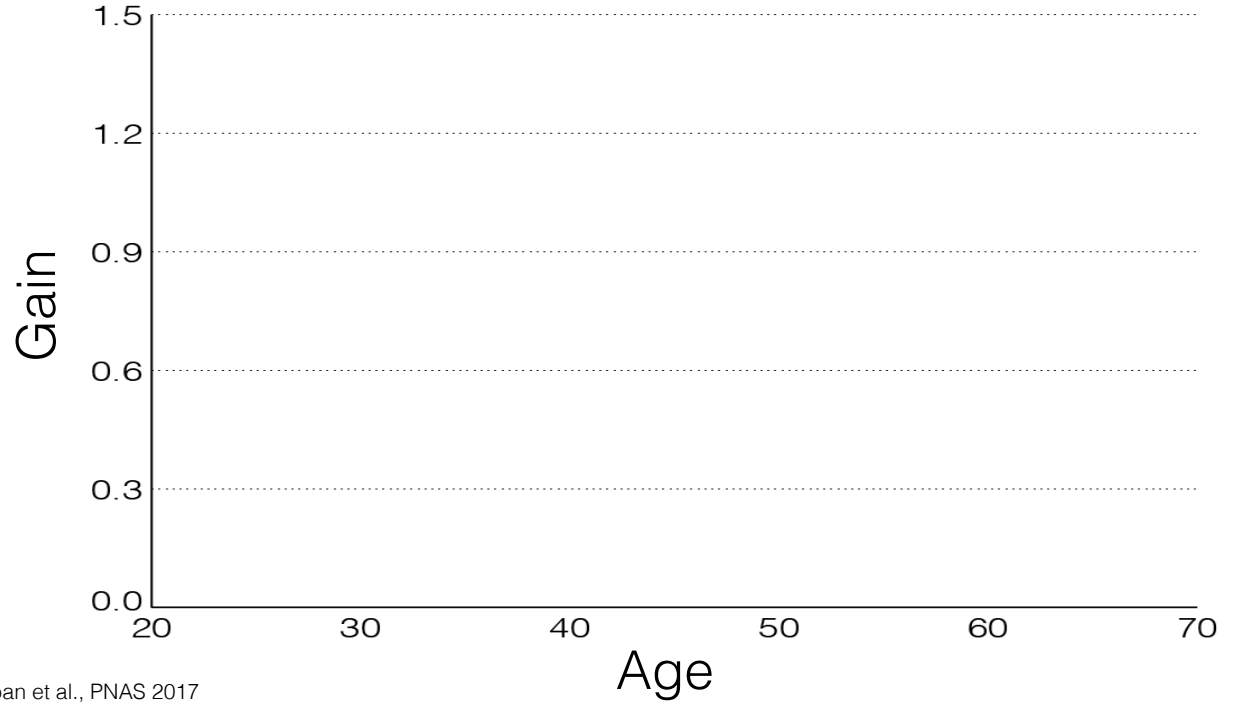
Accommodative Response





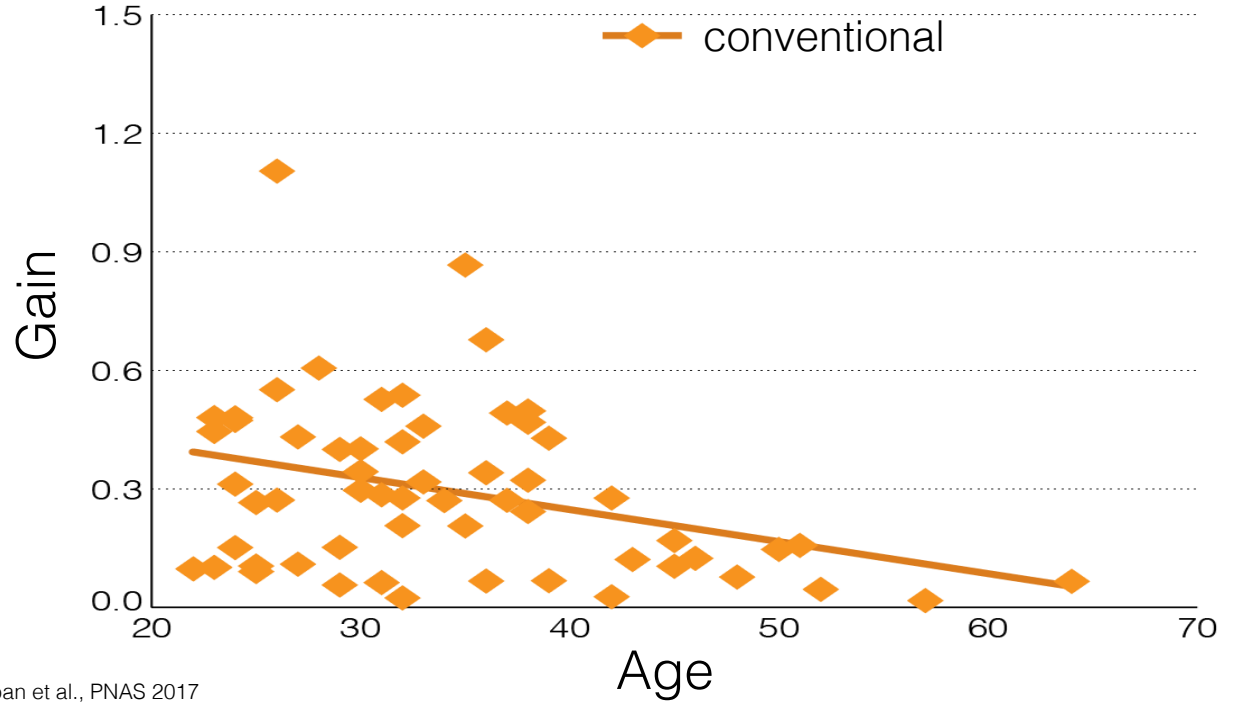
Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?



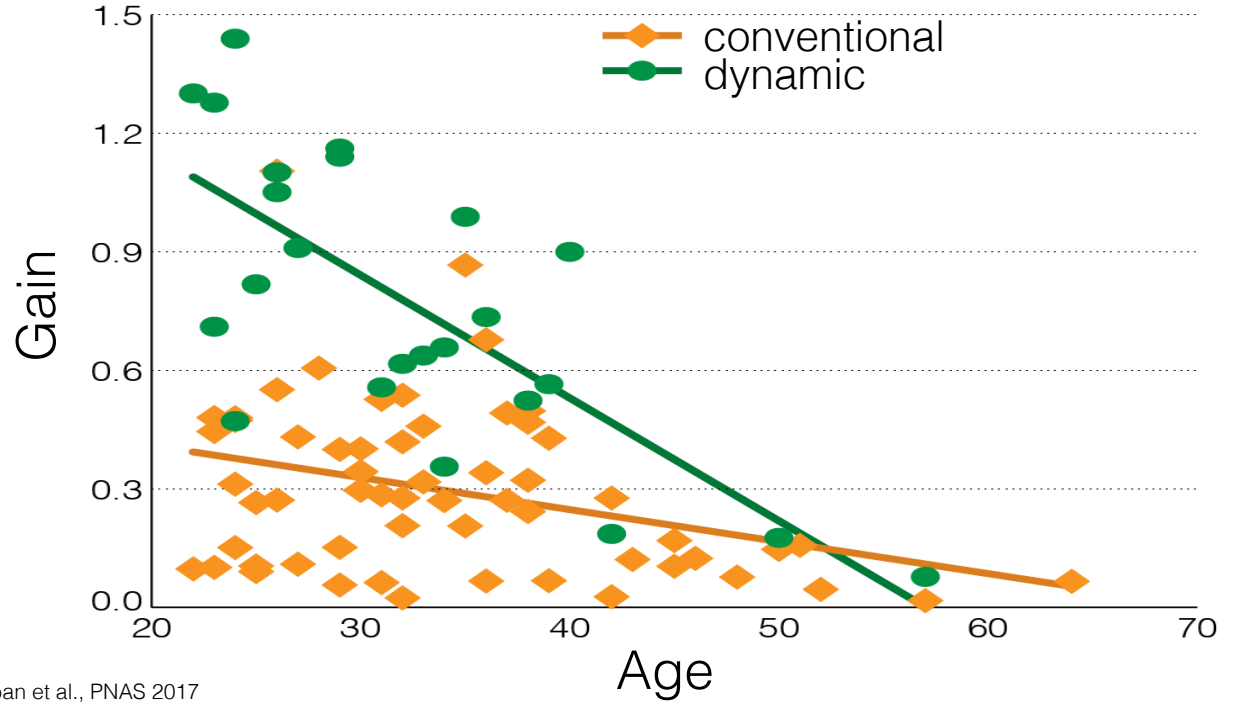
Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?



Padmanaban et al., PNAS 2017

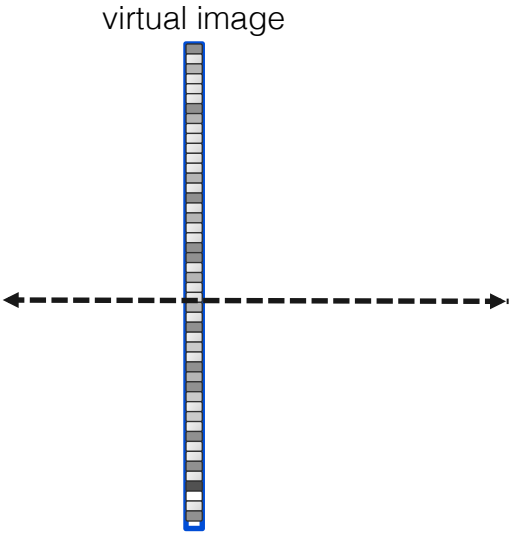
Do Presbyopes Benefit from Dynamic Focus?

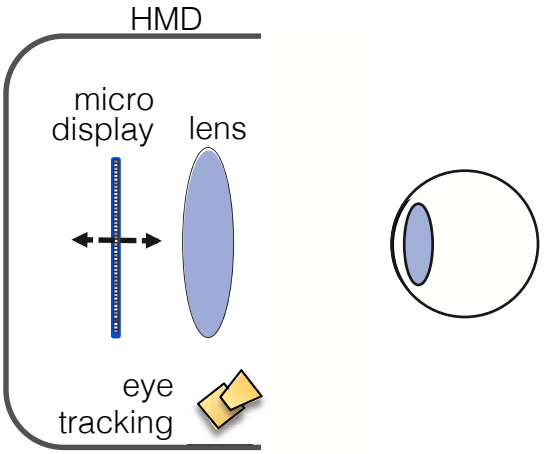


Padmanaban et al., PNAS 2017

Gaze-contingent Focus

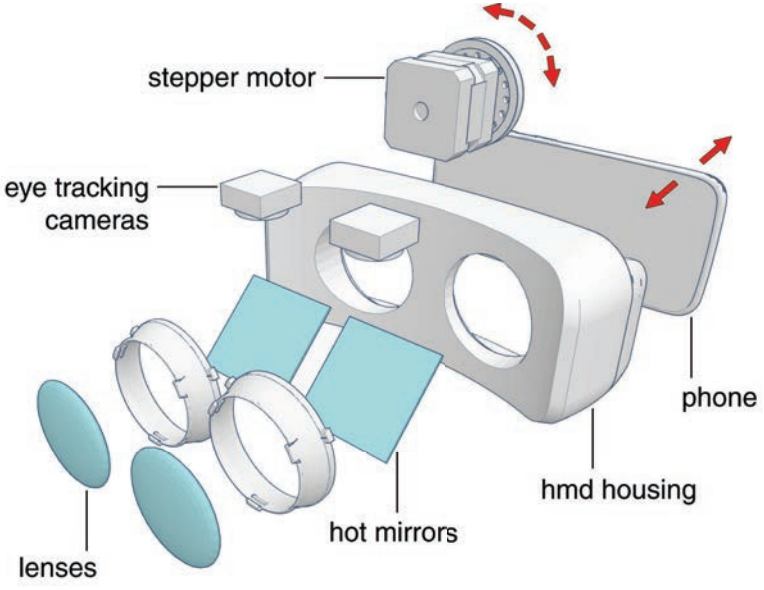
- non-presbyopes: adaptive focus is like real world, but needs eye tracking!





Padmanaban et al., PNAS 2017

Gaze-contingent Focus

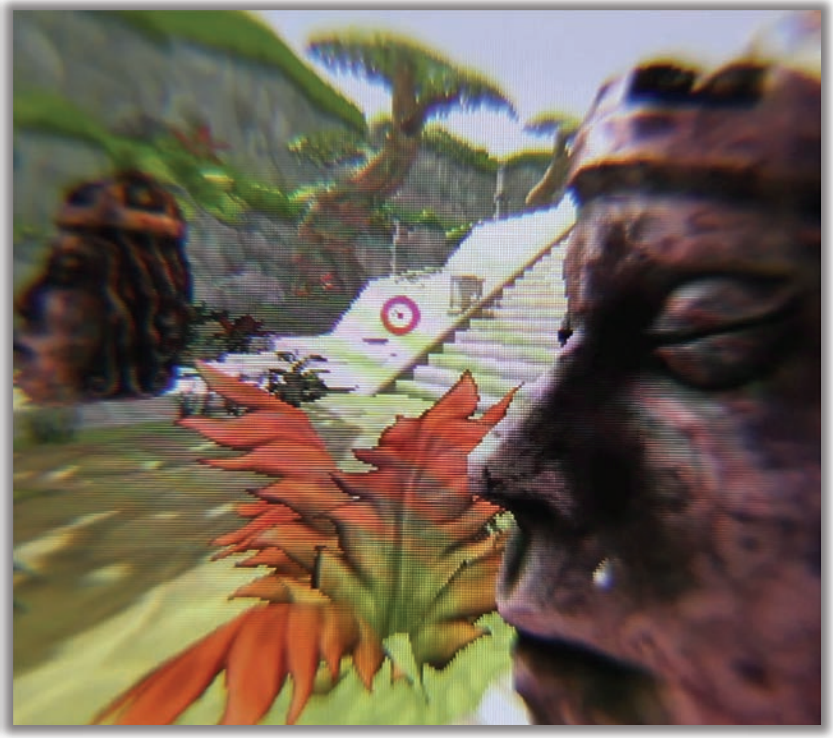


Padmanaban et al., PNAS 2017

Gaze-contingent Focus

Padmanaban et al., PNAS 2017

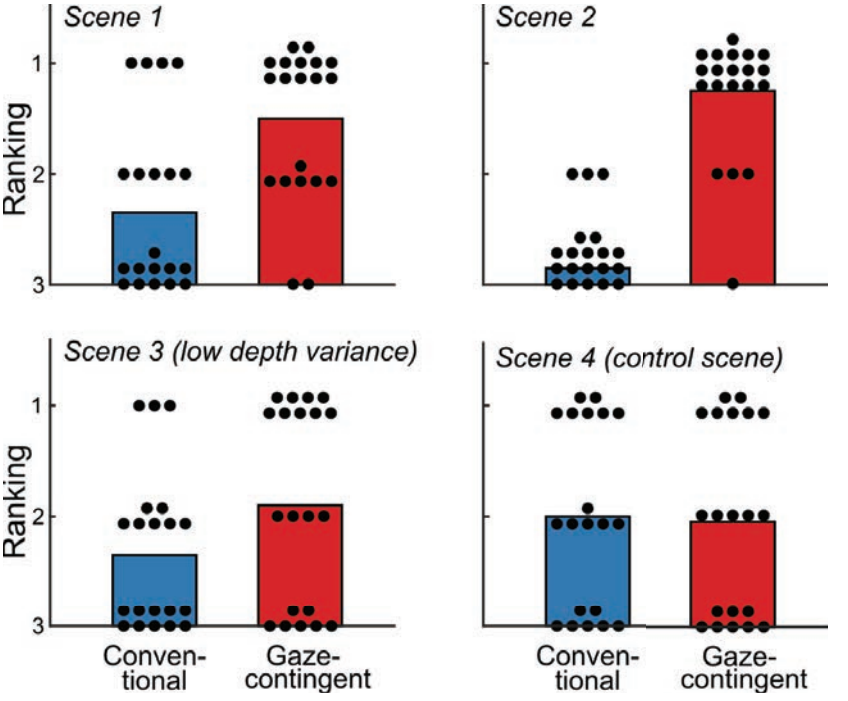
Gaze-contingent Focus



Padmanaban et al., PNAS 2017

at ACM SIGGRAPH 2016

Gaze-contingent Focus – User Preference

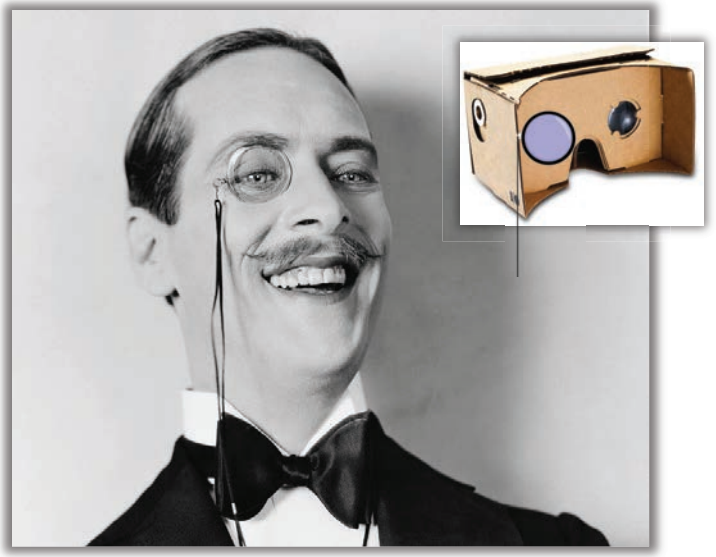


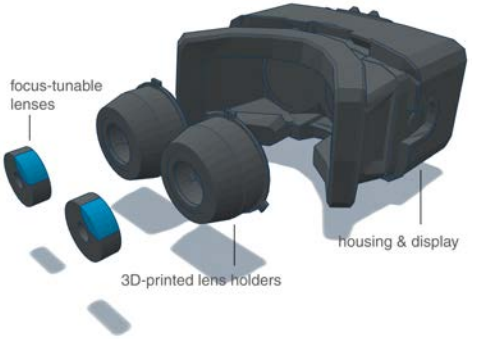
Padmanaban et al., PNAS 2017

VR Displays with Focus Cues

2. Monovision

Monovision VR

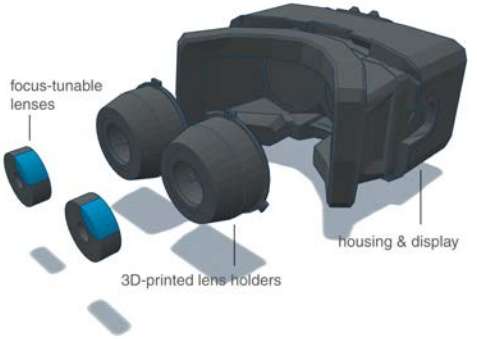


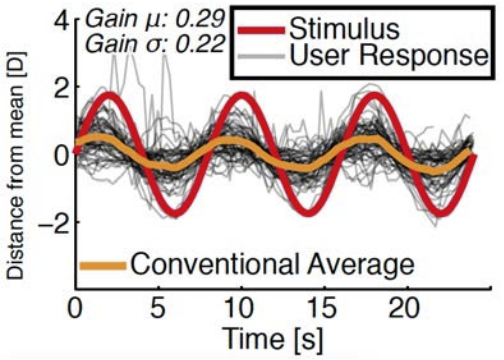


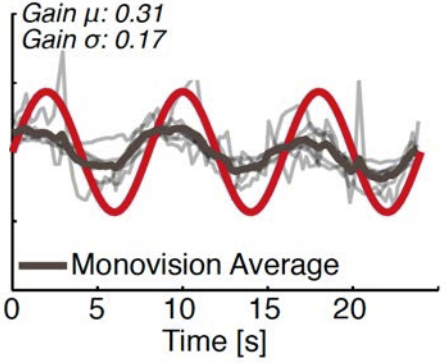
Konrad et al., SIGCHI 2016; Johnson et al., Optics Express 2016; Padmanaban et al., PNAS 2017

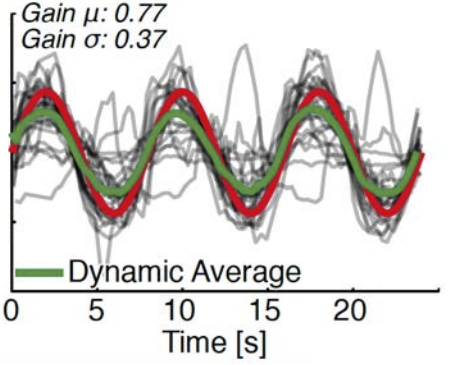
Monovision VR

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







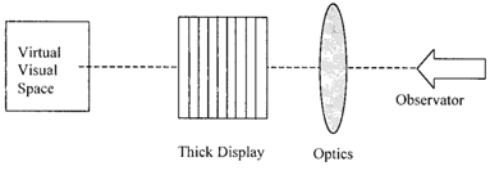


Konrad et al., SIGCHI 2016; Johnson et al., Optics Express 2016; Padmanaban et al., PNAS 2017

VR Displays with Focus Cues

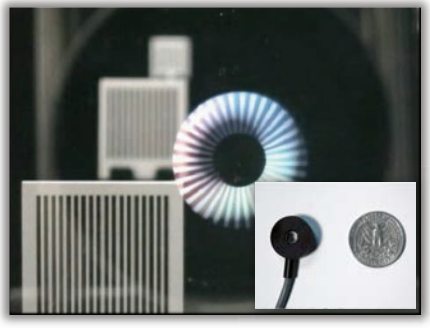
3. Multiplane Displays

Multiplane VR Displays



idea introduced
Rolland et al. 2000

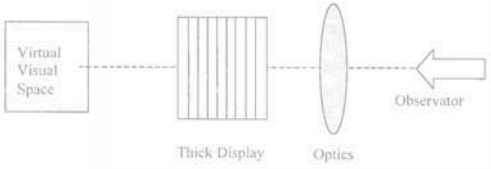
benchtop prototype
Akeley 2004



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)
- 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 ...

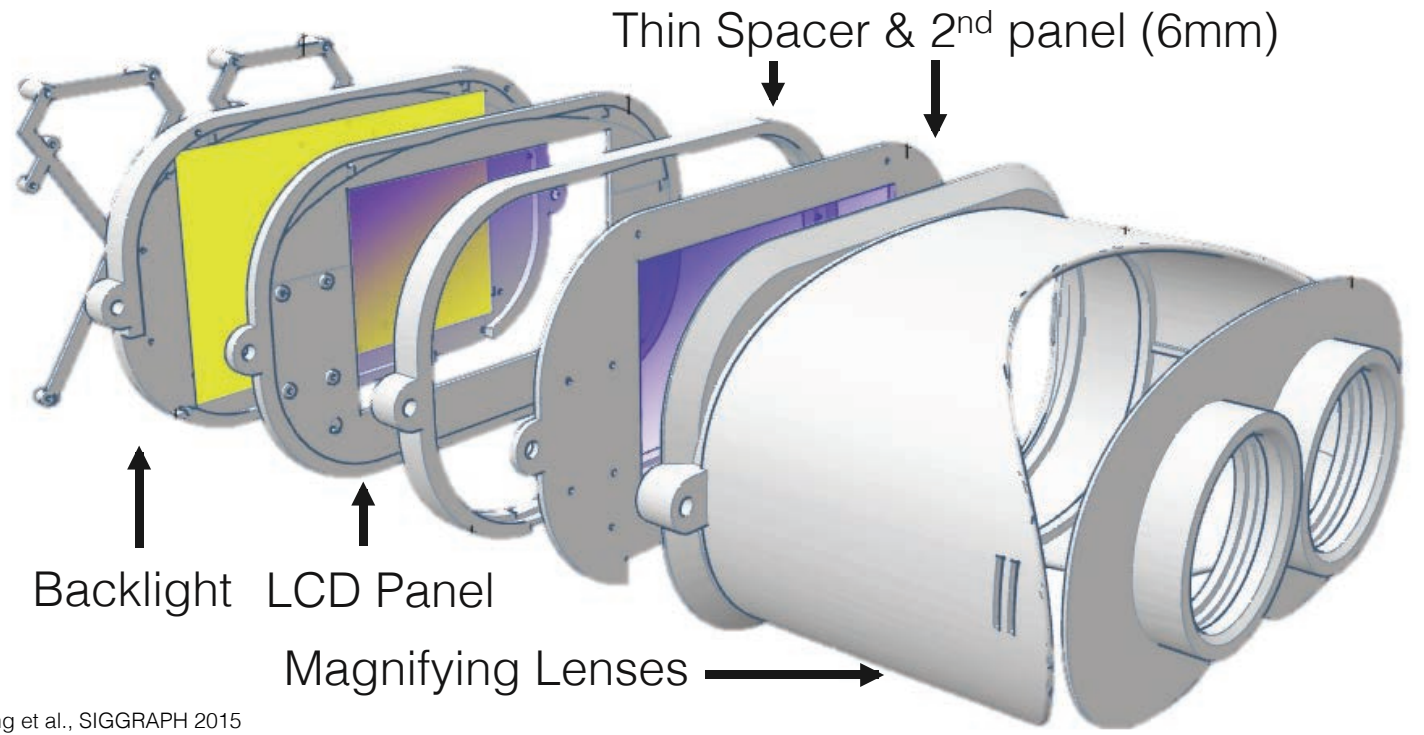
VR Displays with Focus Cues

4. Light Field Displays

Light Field Stereoscope

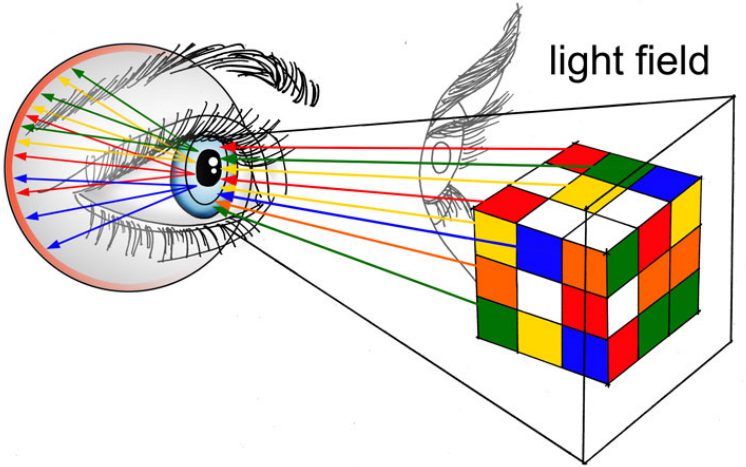
Huang et al., SIGGRAPH 2015

Light Field Stereoscope



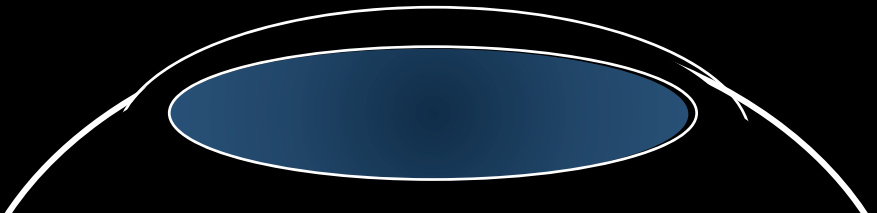
Huang et al., SIGGRAPH 2015

Near-eye Light Field Displays

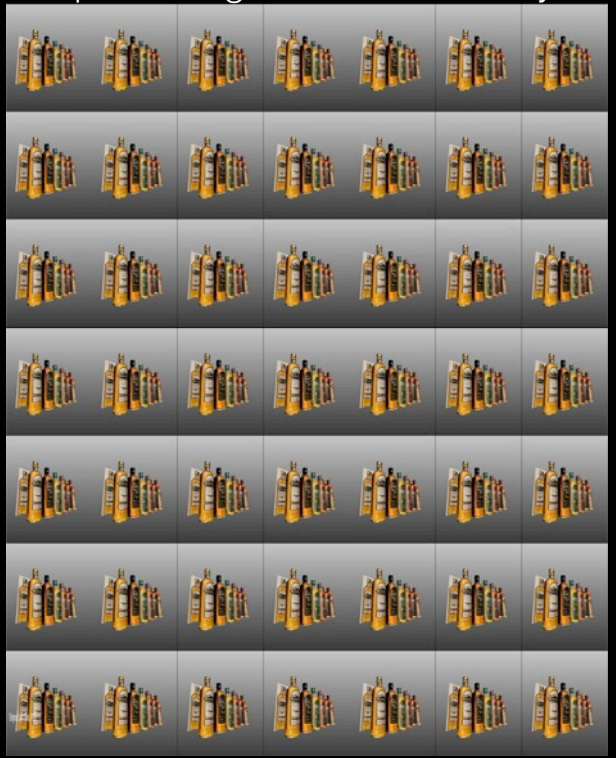


Idea: project multiple different perspectives into different parts of the pupil!

Target Light Field

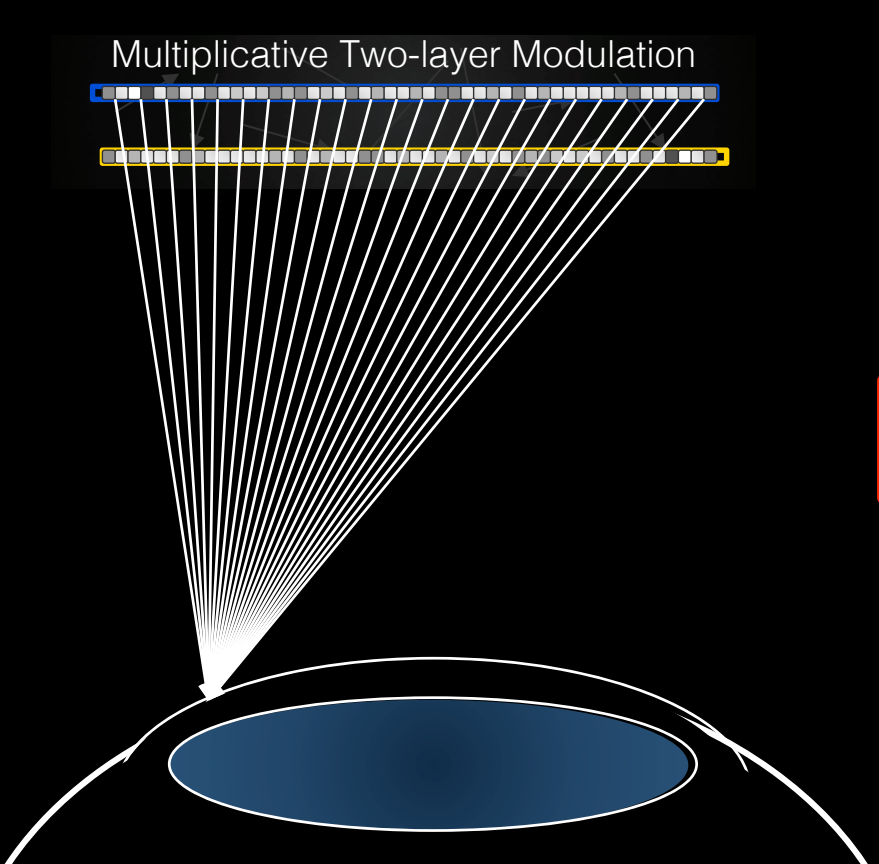


Input: 4D light field for each eye

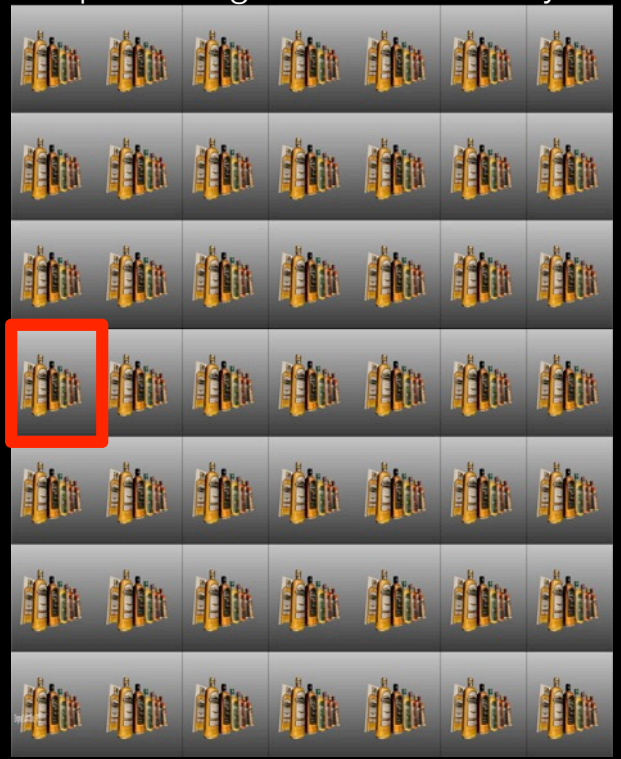


Model Courtesy of **Bushmills** Irish Whiskey

Multiplicative Two-layer Modulation

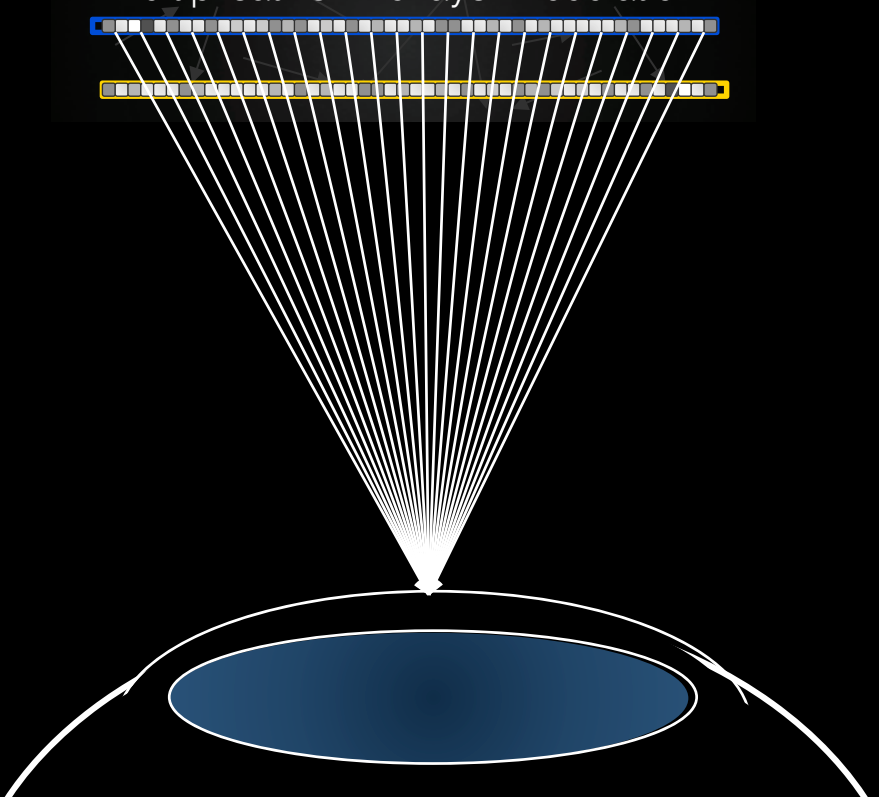


Input: 4D light field for each eye

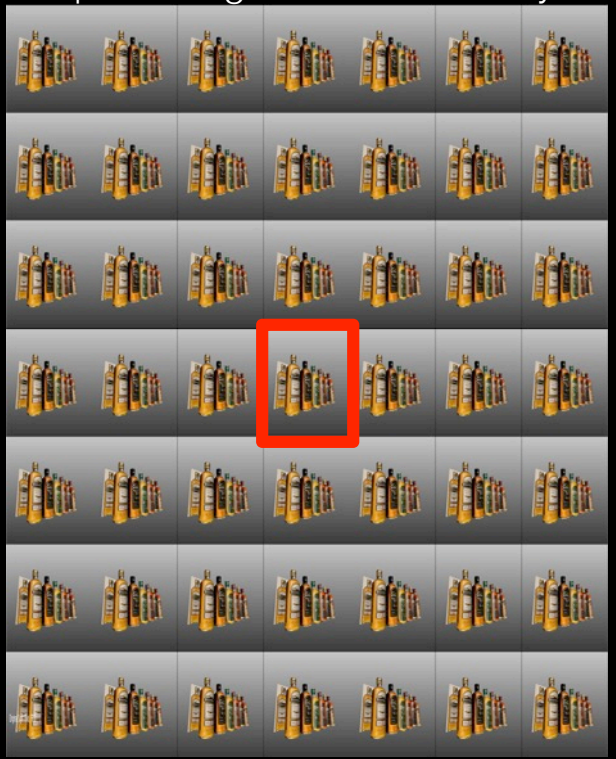


Model Courtesy of **Bushmills** Irish Whiskey

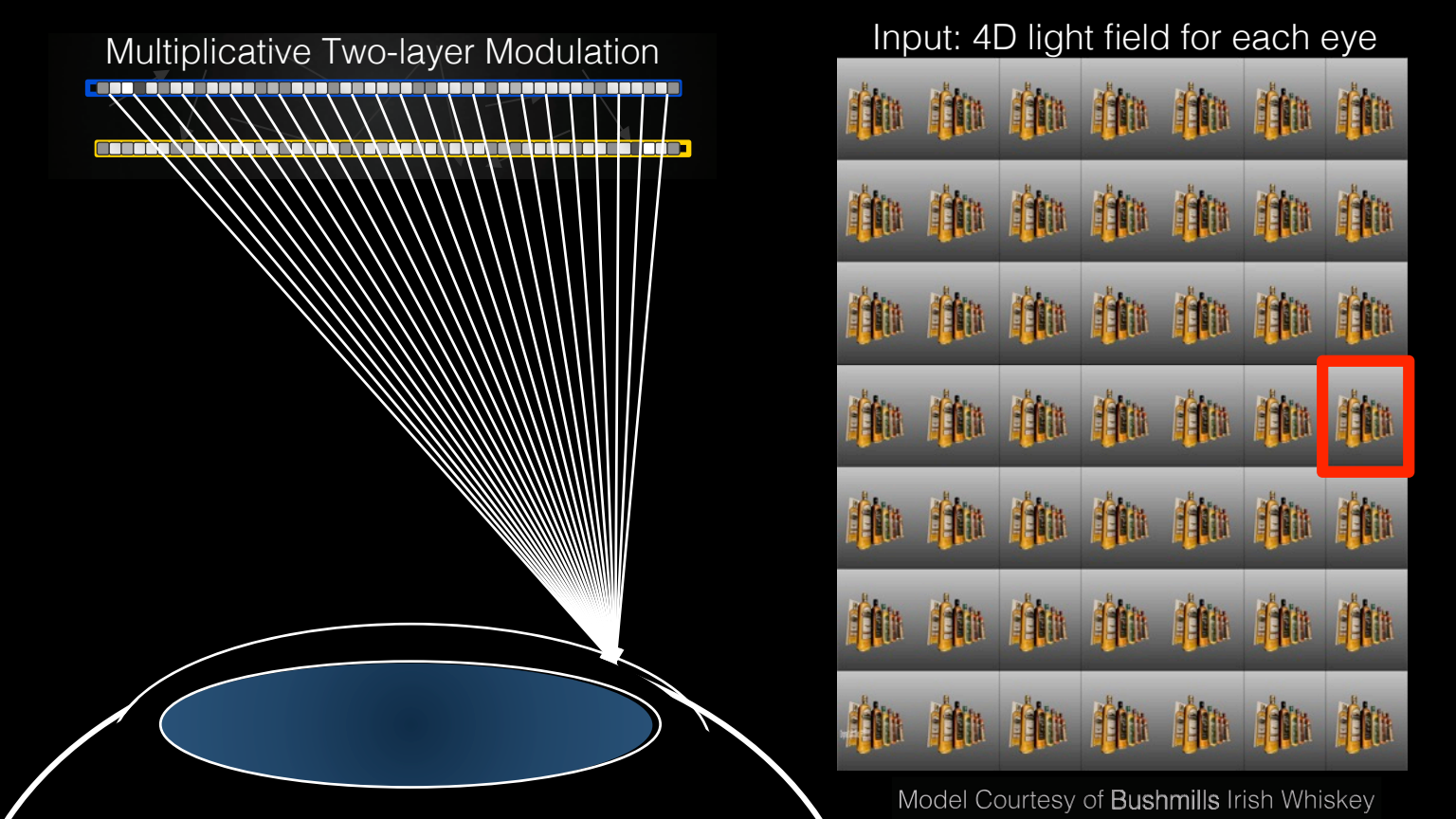
Multiplicative Two-layer Modulation



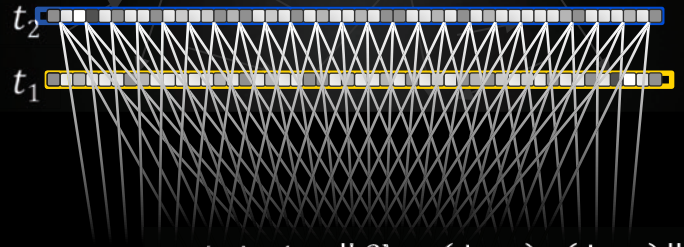
Input: 4D light field for each eye



Model Courtesy of **Bushmills** Irish Whiskey


Multiplicative Two-layer Modulation
Input: 4D light field for each eye
Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation



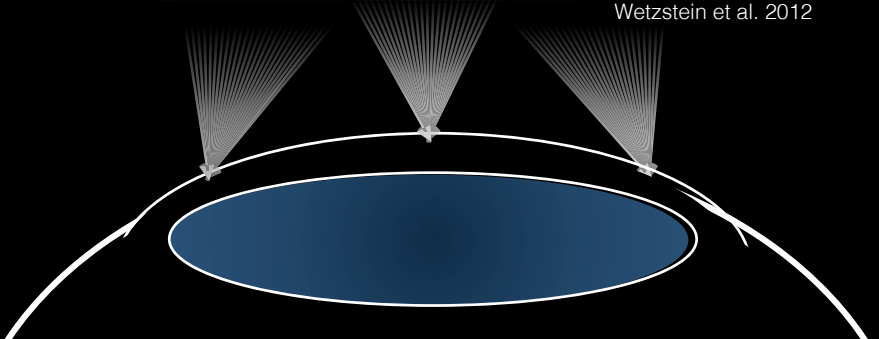
$$\underset{\{t_1,t_2\}}{minimize} \; \|\beta \mathbf{l} - (\phi_1 t_1) \mathrm{o} (\phi_2 t_2)\|^2 \quad s.t.\ 0 \le t_1, t_2 \le 1$$

Reconstruction:

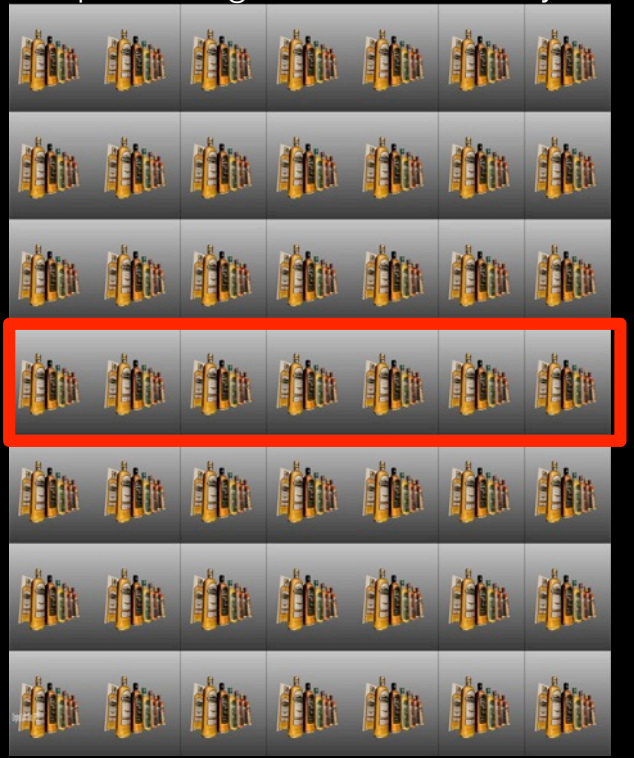
$$t_1 \leftarrow t_1 \, \mathrm{o} \, \frac{\phi_1^T(\beta \mathbf{l} \, \mathrm{o} \, (\phi_2 t_2))}{\phi_1^T\left(\tilde{\mathbf{l}} \, \mathrm{o} \, (\phi_2 t_2)\right) + \epsilon}$$

for layer t_1

Tensor Displays, Wetzstein et al. 2012

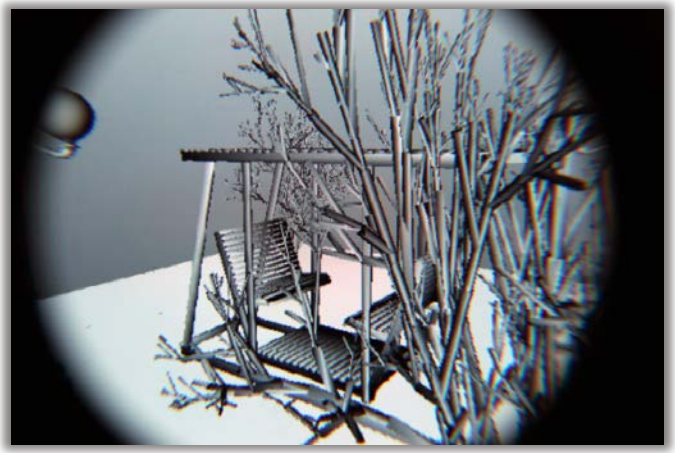


Input: 4D light field for each eye



Model Courtesy of **Bushmills** Irish Whiskey

Light Field Stereoscope

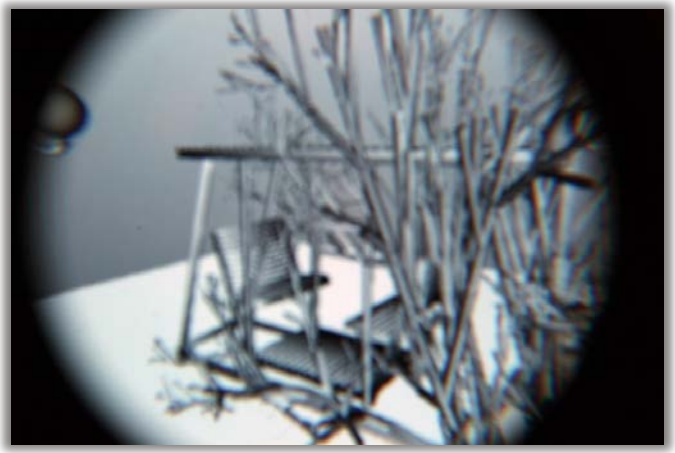


Traditional HMDs
- No Focus Cues

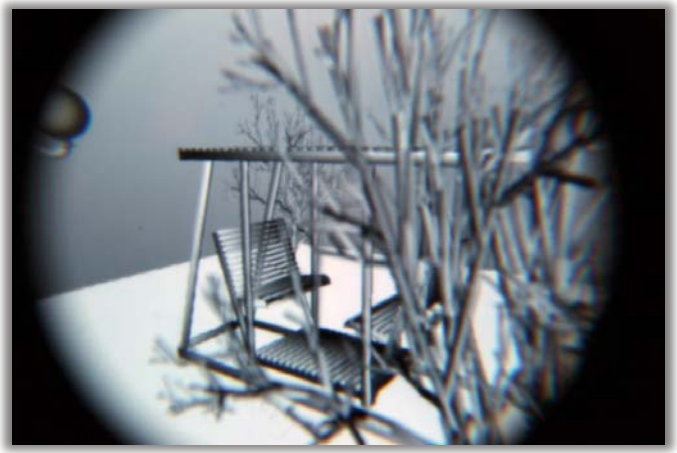
The Light Field HMD
Stereoscope

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



Traditional HMDs
- No Focus Cues



The Light Field HMD
Stereoscope

Huang et al., SIGGRAPH 2015

Light Field Stereoscope

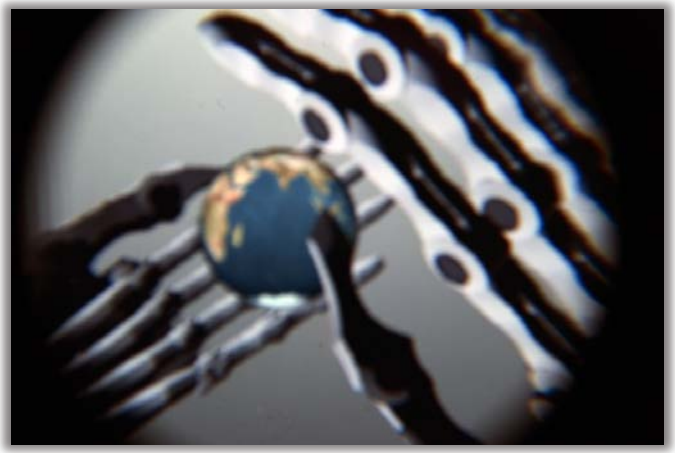
Traditional HMDs
- No Focus Cues

The Light Field HMD
Stereoscope

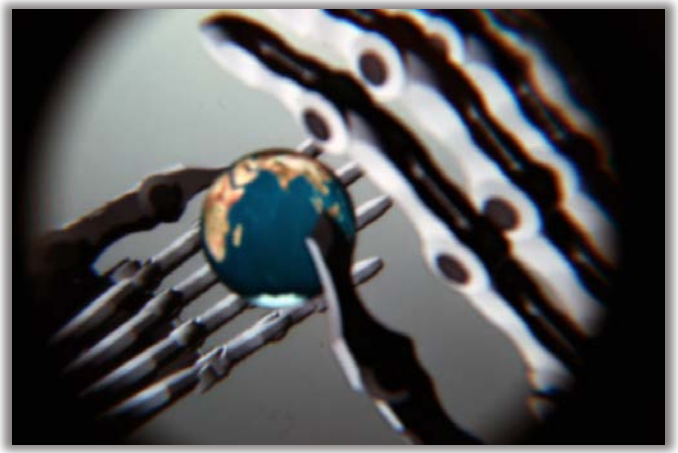
Model Courtesy of Paul H. Manning

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



Traditional HMDs
- No Focus Cues

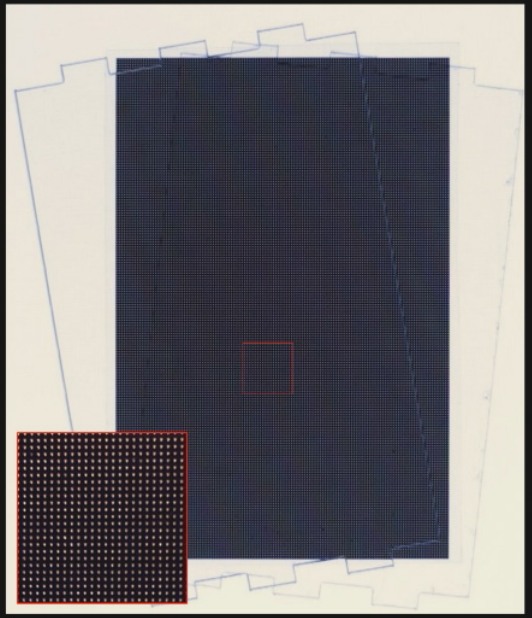


The Light Field HMD
Stereoscope

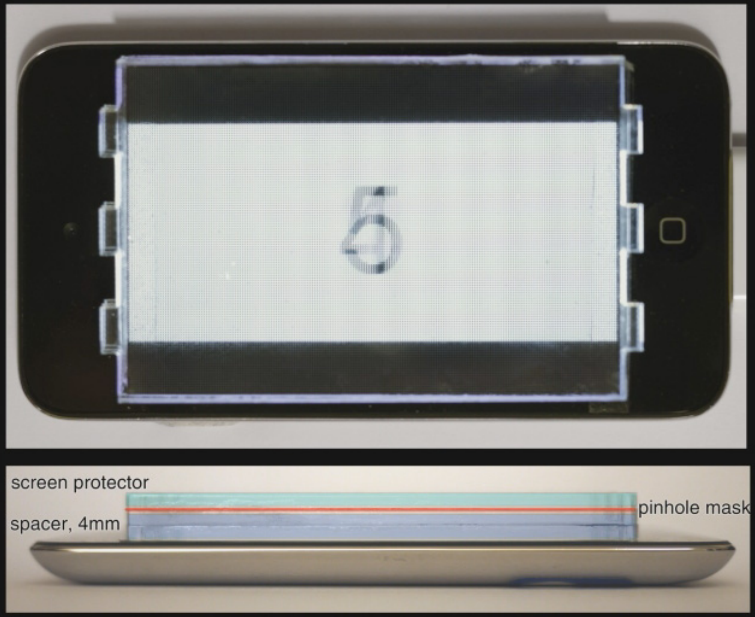
Model Courtesy of Paul H. Manning

Huang et al., SIGGRAPH 2015

Vision-correcting Display



printed transparency



iPod Touch prototype

Huang et al., SIGGRAPH 2014

prototype

300 dpi or higher

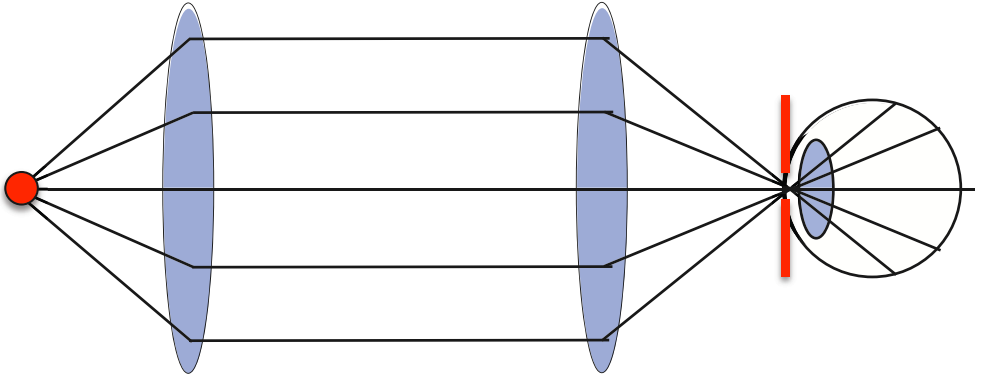
Huang et al., SIGGRAPH 2014

VR Displays with Focus Cues

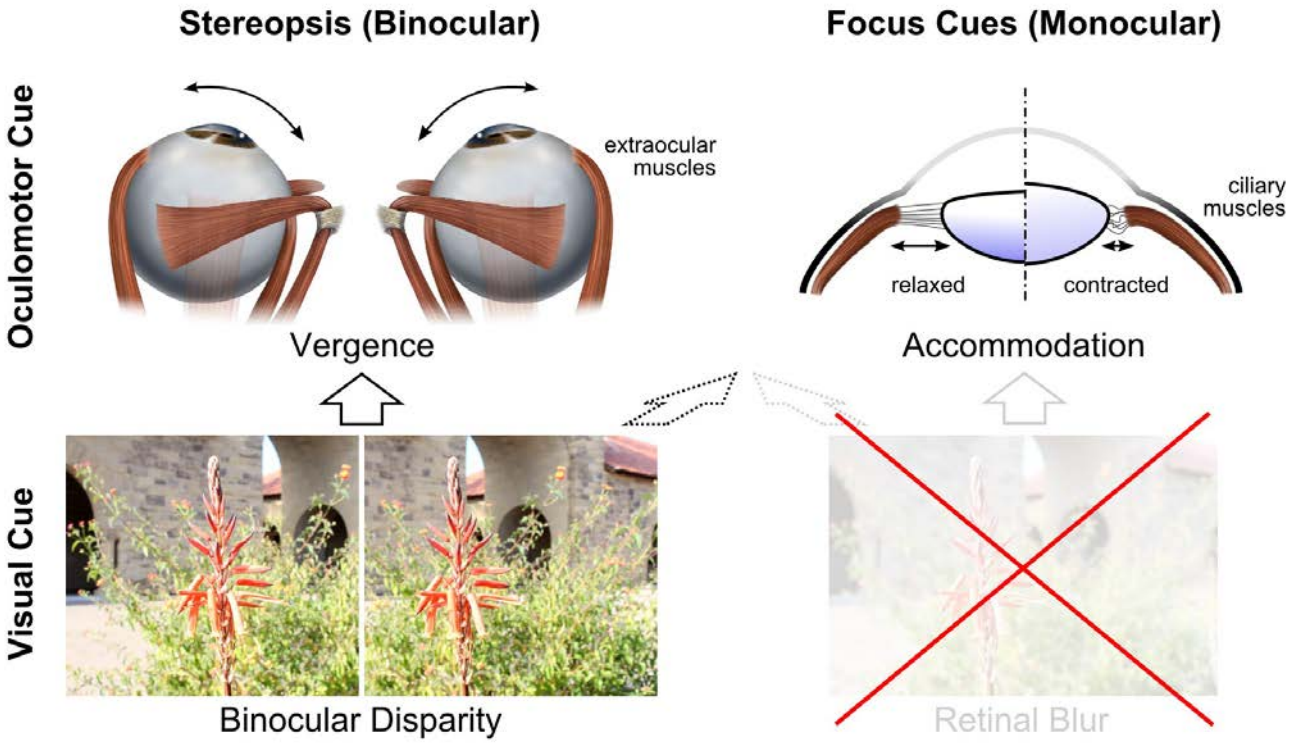
5. Maxwellian-type Displays

Maxwellian-type Near-eye Displays

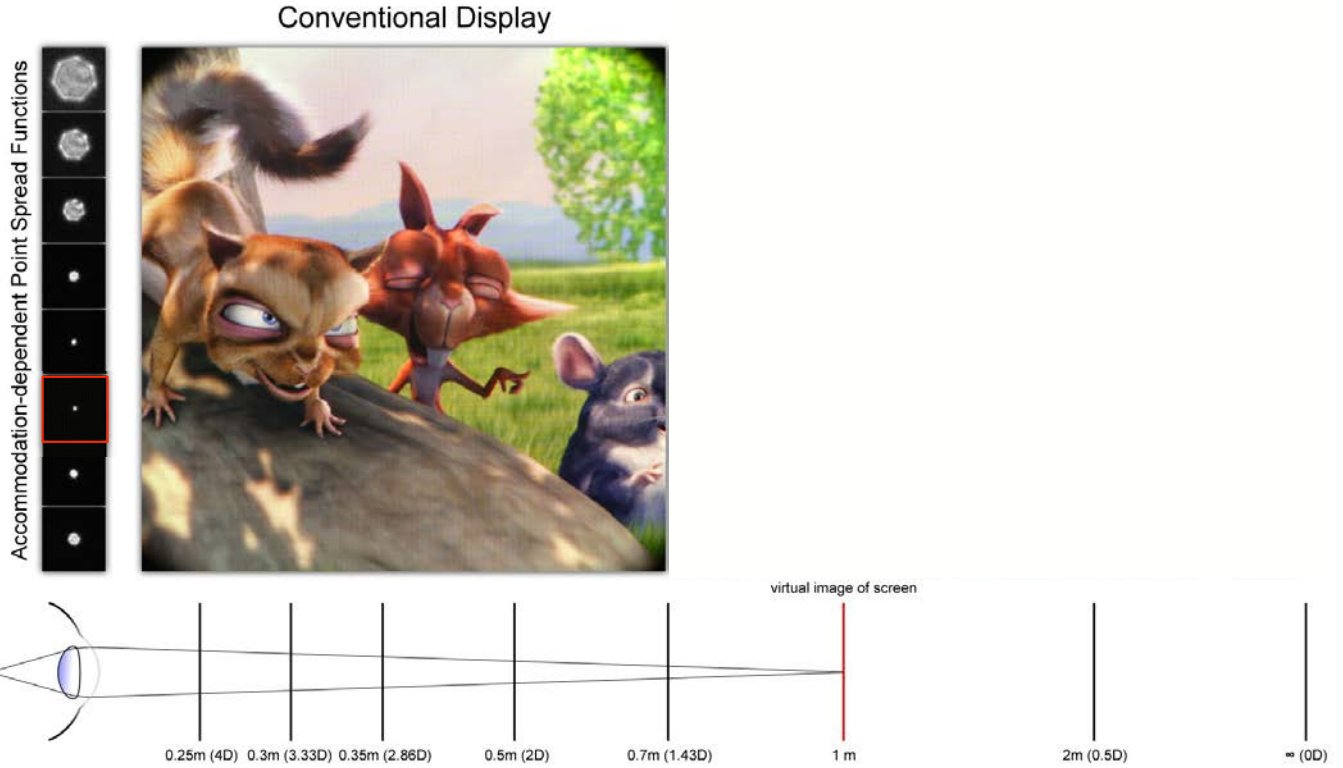
- eyebox of display is a pinhole → very large depth of field (no retinal blur cue)
- exit pupil size of ≤0.5 mm → accommodation in open loop
- pinholes are dim and reduce eyebox severely! (not practical)



Maxwellian-type Near-eye Displays

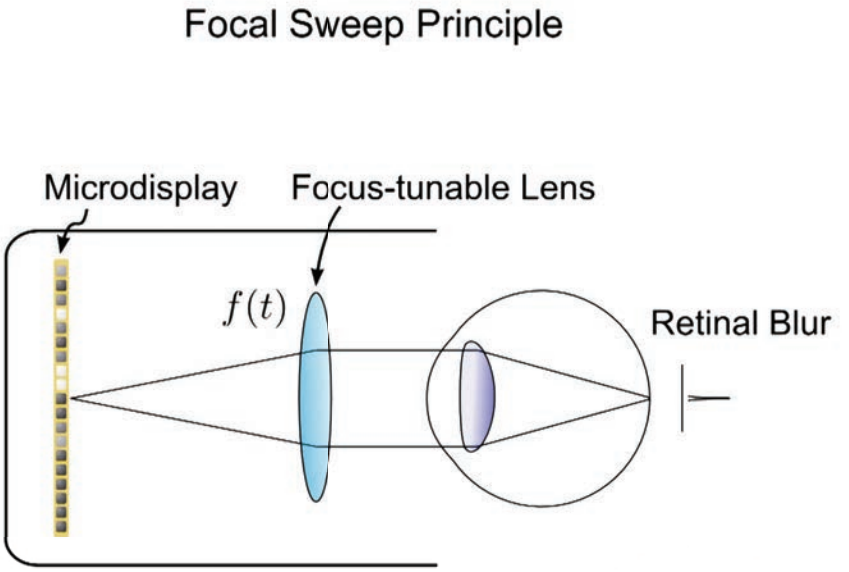


Accommodation-invariant Near-eye Displays



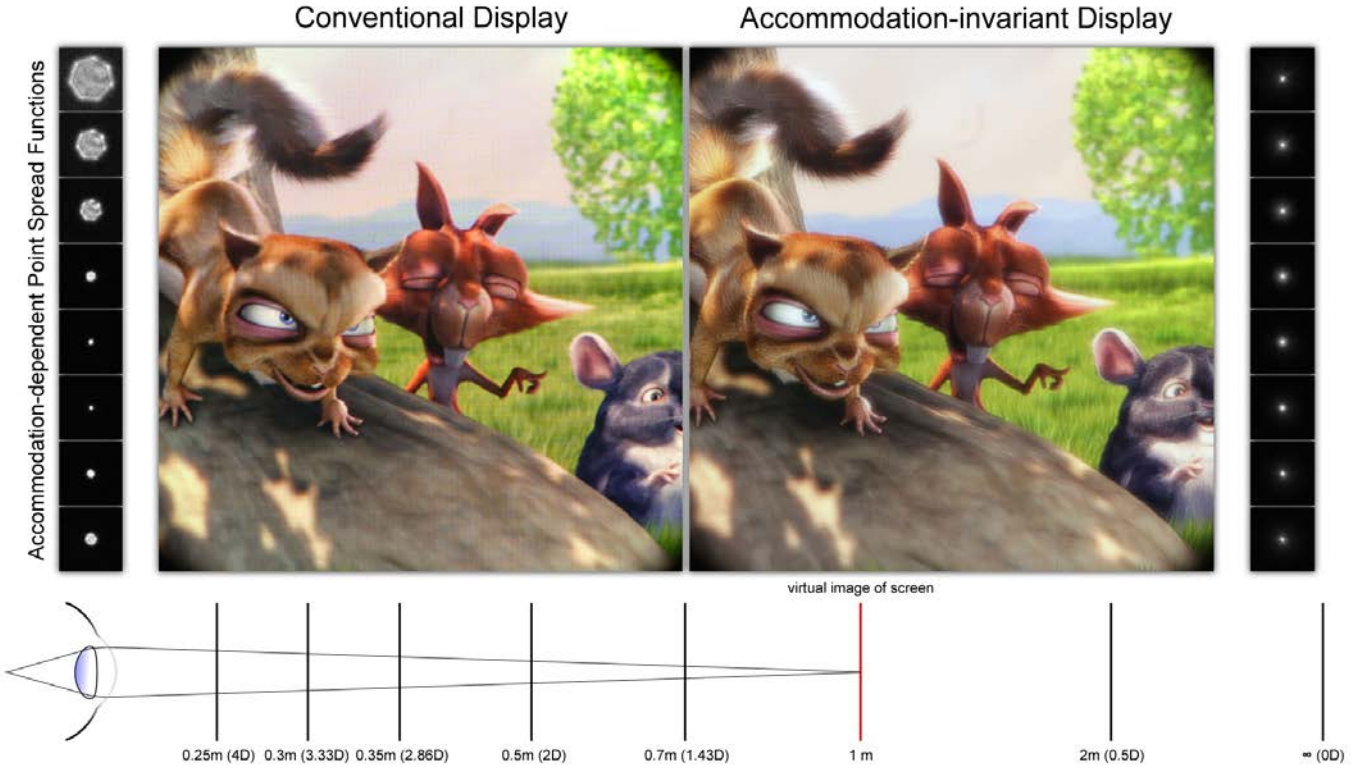
Konrad et al., SIGGRAPH 2017

Accommodation-invariant Near-eye Displays



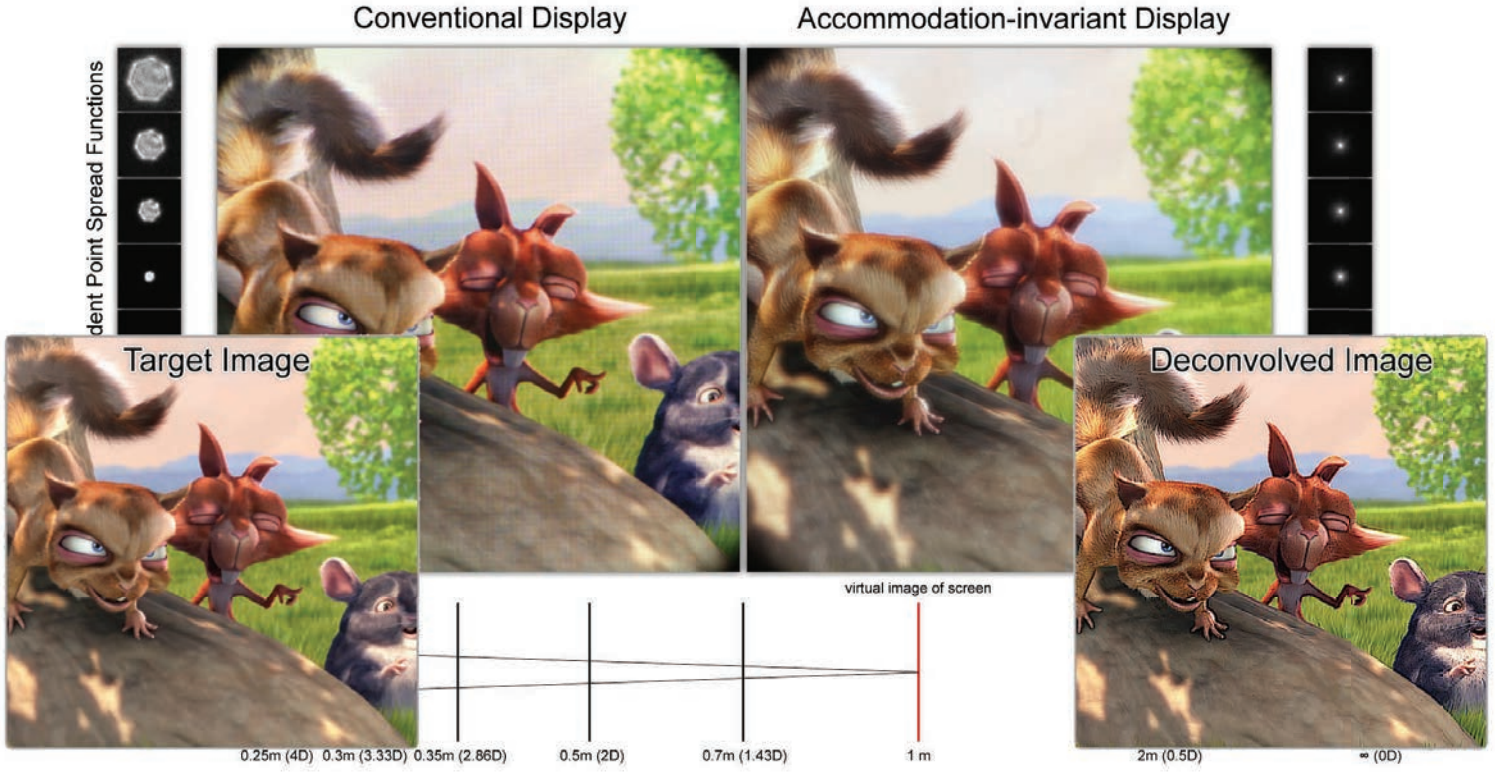
Konrad et al., SIGGRAPH 2017

Accommodation-invariant Near-eye Displays



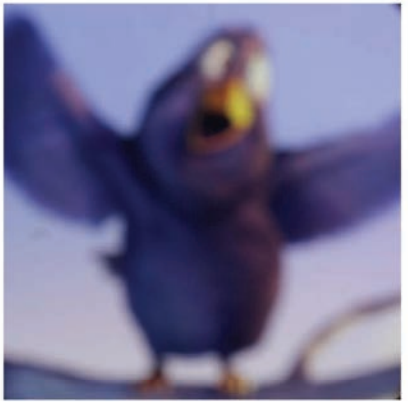
Konrad et al., SIGGRAPH 2017

Accommodation-invariant Near-eye Displays



Accommodation-invariant Near-eye Displays

Conventional



Konrad et al., SIGGRAPH 2017

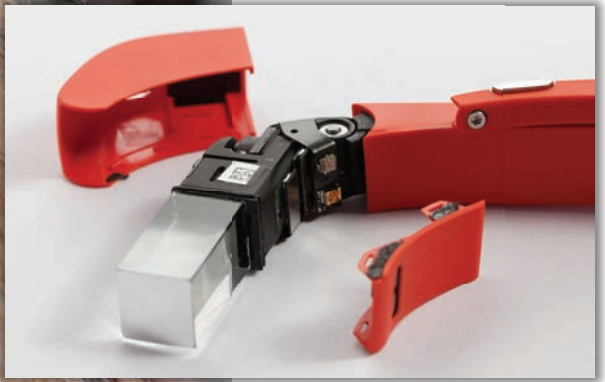
Overview of Optical See-through AR Displays

Consumer Applications – Prescription Glasses

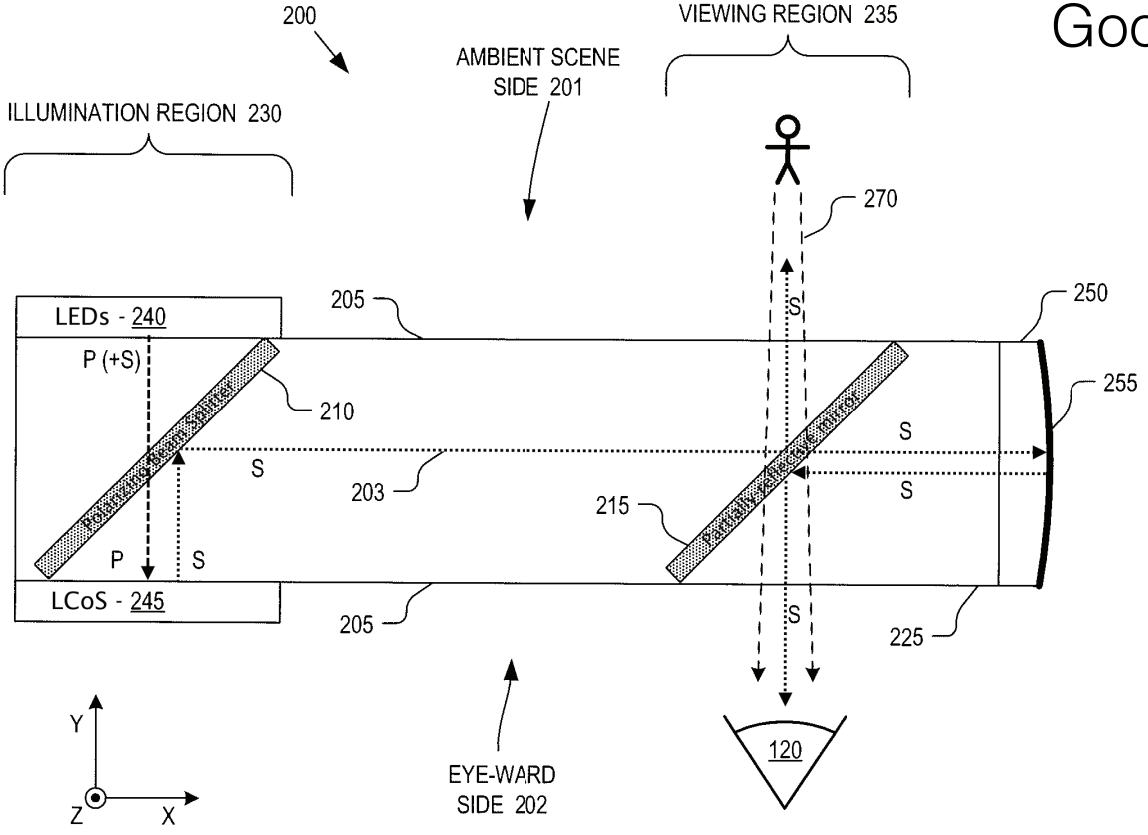
slide by Bernard Kress

Google Glass

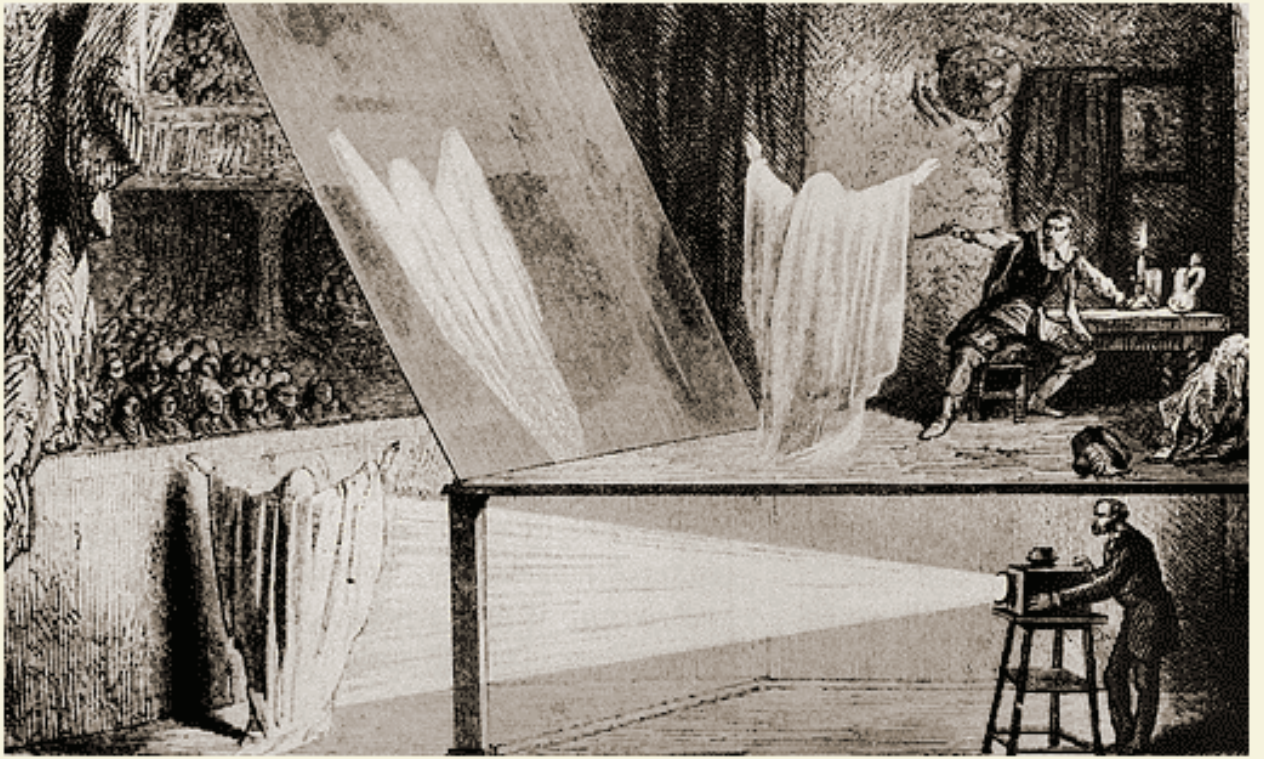
small!



Google Glass

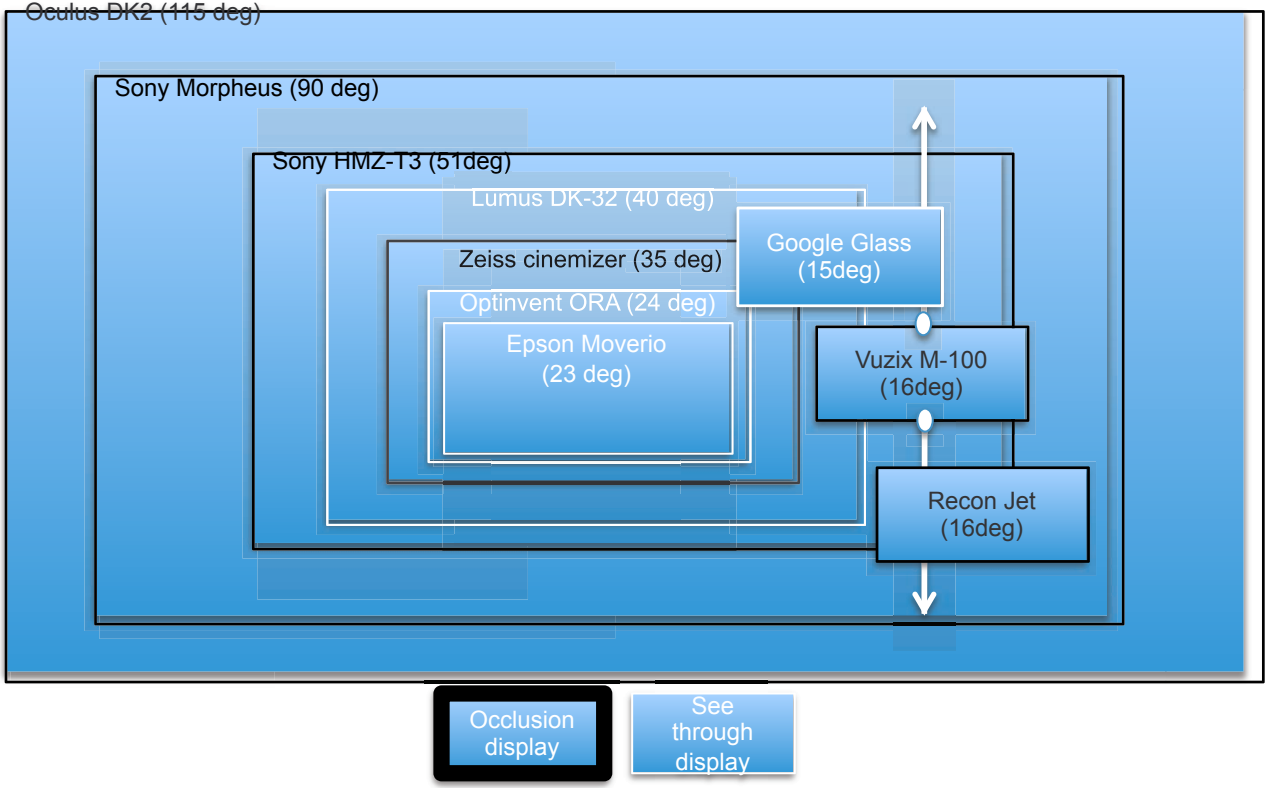


Pepper's Ghost 1862



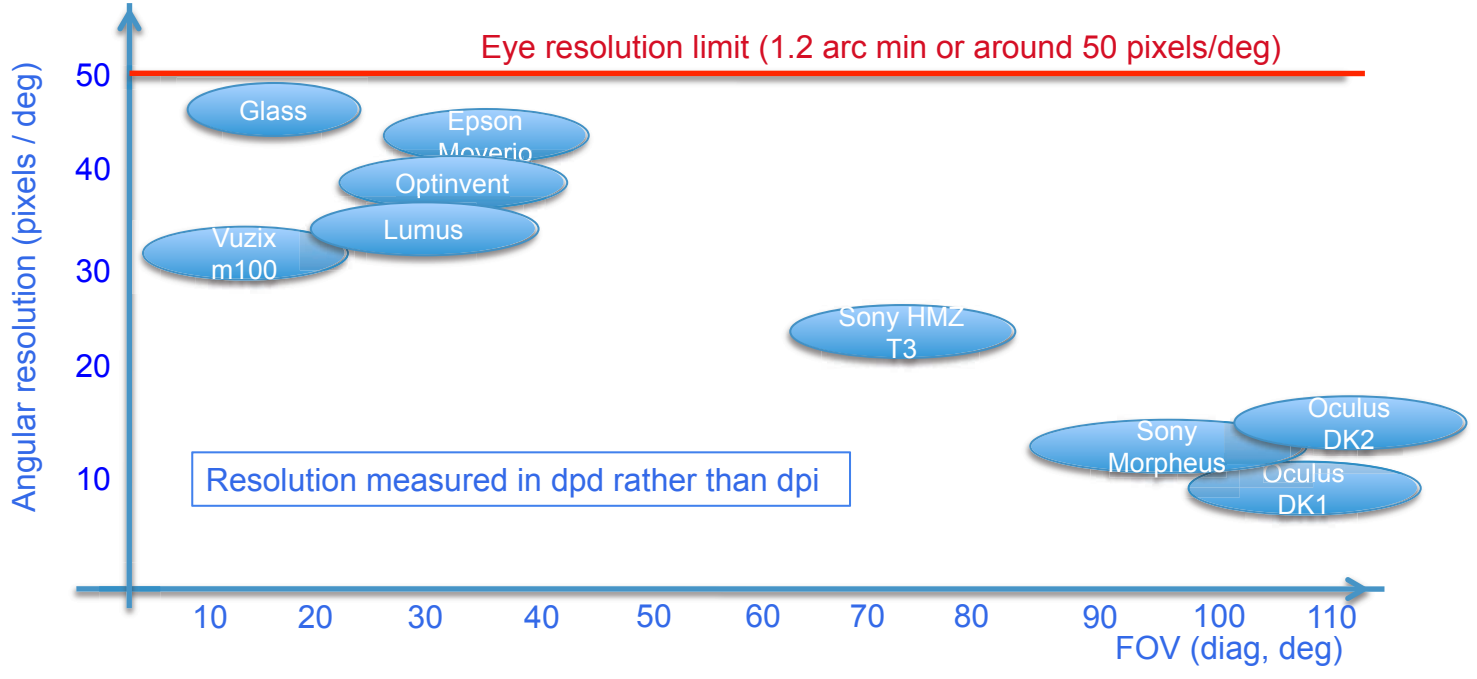
Microsoft Hololens – Waveguide with Holographic Optical Elements

FOV (diag) and FOV location in some of the current products



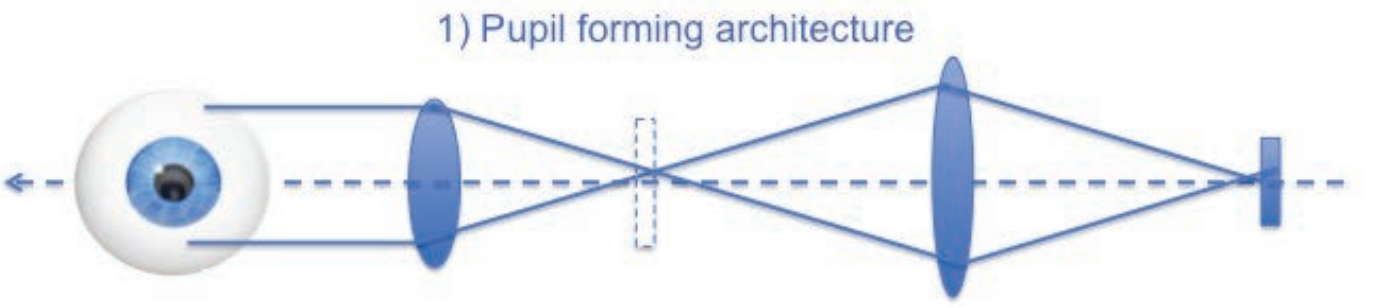
slide by Bernard Kress

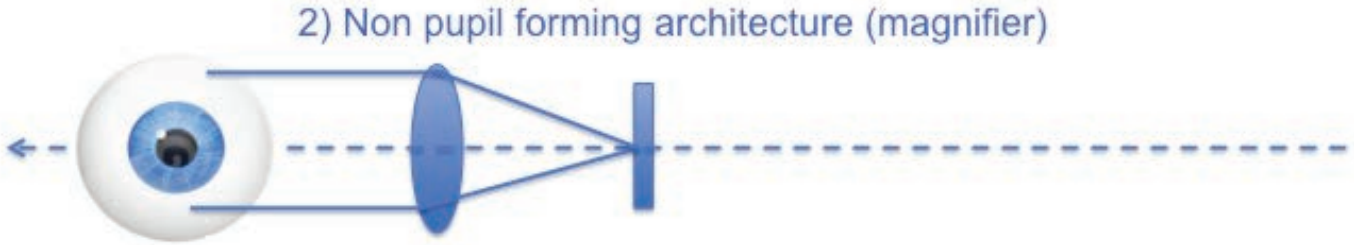
FOV and angular resolution for current products



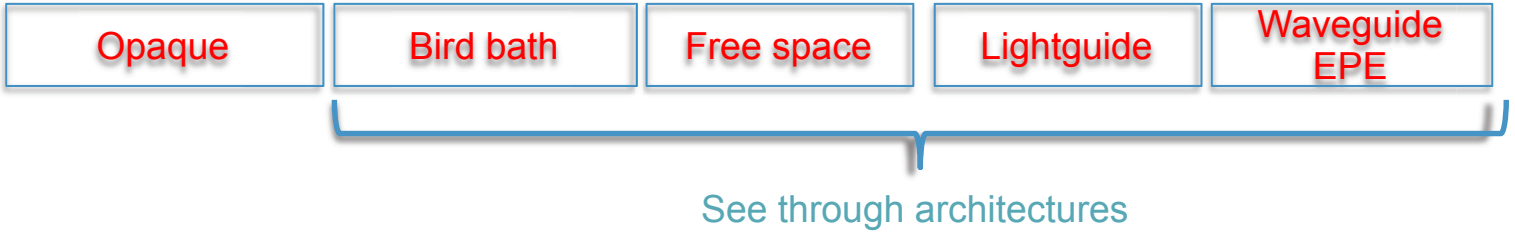
slide by Bernard Kress

There are two main optical HMD architectures





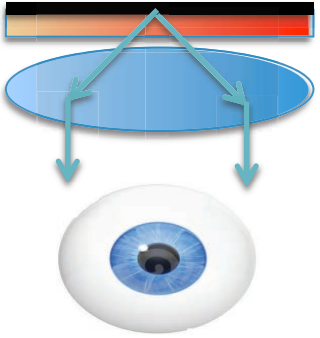
slide by Bernard Kress



There are 5 main head-worn optical platform architectures developed in industry today

slide by Bernard Kress

Opaque | Bird bath | Free space | Lightguide | Waveguide EPE

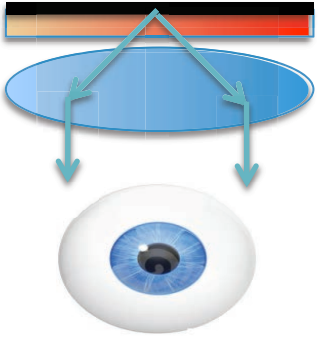


Oculus DK2 Sony HMZ Vuzix	Occlusion Huge FOV Large eyebox

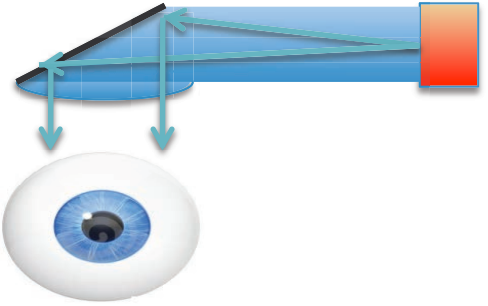
slide by Bernard Kress

slide by Bernard Kress

Opaque | Bird bath | Free space | Lightguide | Waveguide EPE



Oculus DK2 Sony HMZ Vuzix	Occlusion Huge FOV Large eyebox



Vuzix M100 MyVu …	Partially occluded Small FOV Medium eye box

slide by Bernard Kress

Most of the early occlusion HMDs are based on the combination of a transmission lens and a 45 degrees mirror (either TIR or coated) , in either monocular or binocular version.

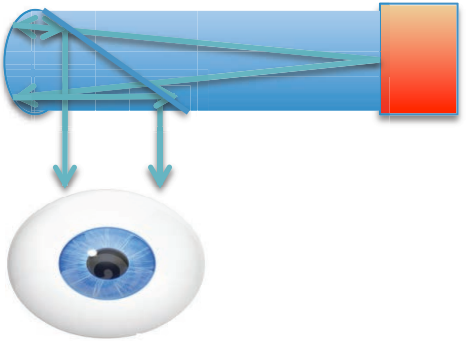
MyVu Corp

Recon Instruments Corp.

MicroOptical Corp. –

slide by Bernard Kress

"Bird bath" optical architectures



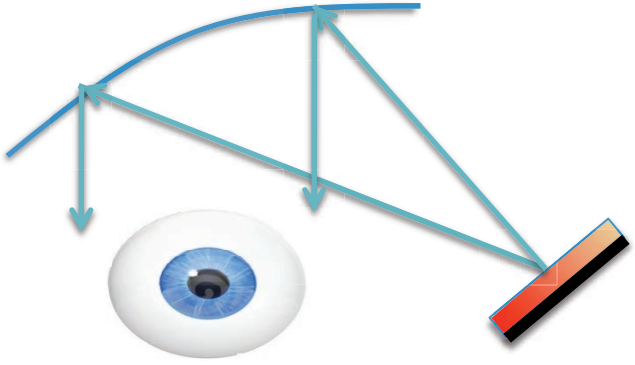
Google Glass RockChip Ltd ITRI	Good see through Small FOV Medium eye box

slide by Bernard Kress

Google Glass

slide by Bernard Kress

Opaque	Bird bath	Free space	Lightguide	Waveguide EPE



Laster Sarl ODA Labs …	Bug eye optics Large FOV Medium eyebox Temple projector

slide by Bernard Kress

The notion of « Bug Eye » in HMD combiner optics

slide by Bernard Kress

This is what we mean with the « bug-eye » concept

Link's AHMD

slide by Bernard Kress

ORA Associates (US)

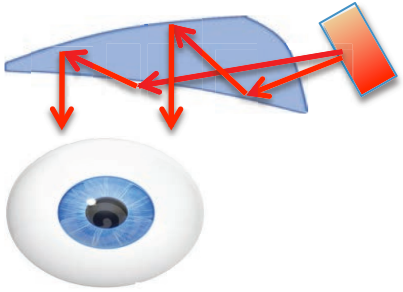
Reflective "bug eye" combiner

Binocular version

Laster Sarl (Fr)

Reflective combiner (pupil forming architecture)

slide by Bernard Kress

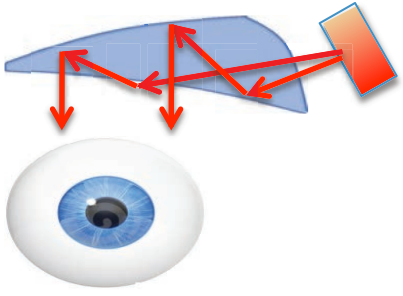


Without complement piece

Canon Ltd Motorola HC1 Kopin Golden eye	Distorted see-through (or opaque) Medium FOV Medium eyebox

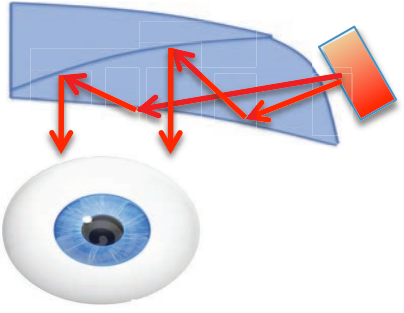
slide by Bernard Kress

Opaque	Bird bath	Free space	Lightguide	Waveguide EPE



Without complement piece

Canon Ltd Motorola HC1 Kopin Golden eye	Distorted see-through (or opaque) Medium FOV Medium eyebox

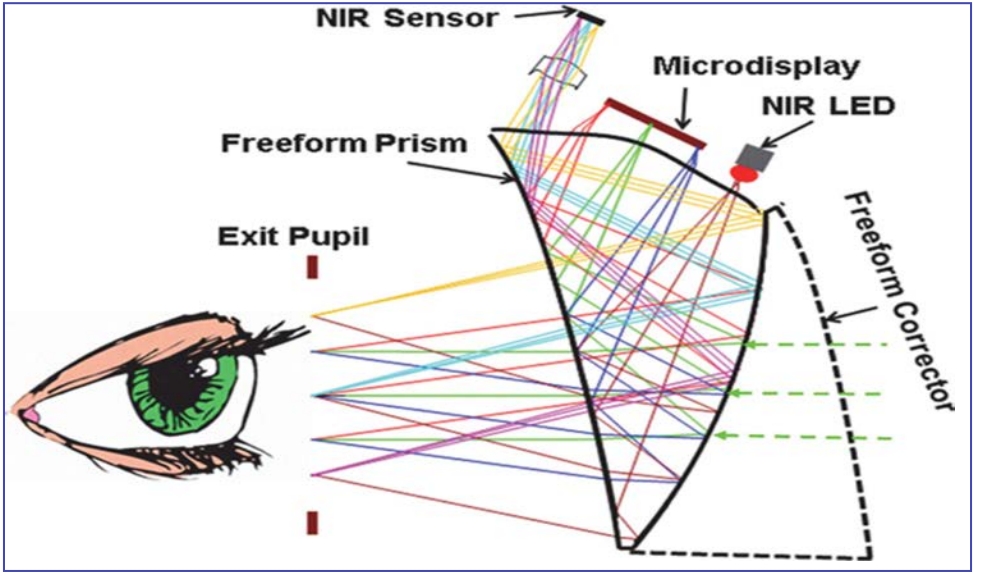


With complement piece

E-Magin Optics Fraunhofer	Good see through Medium FOV Medium eye box

slide by Bernard Kress

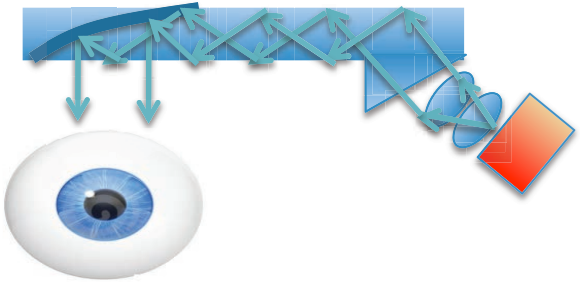
TIR / free-form surfaces combiner (including eye tracking)



[Hua et al. 2013]

Example with complement piece for see through

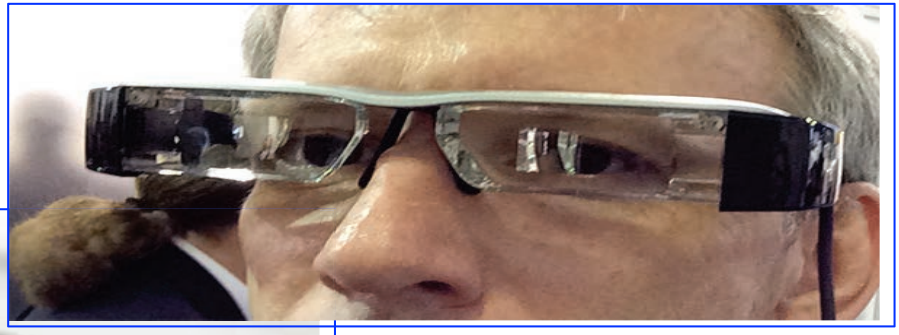
slide by Bernard Kress



Curve coated reflector combiner

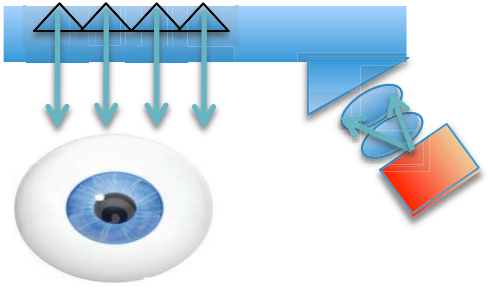
Epson Ltd	OK see through
Moverio 1 & 2	Medium FOV
…	Medium eyebox

slide by Bernard Kress



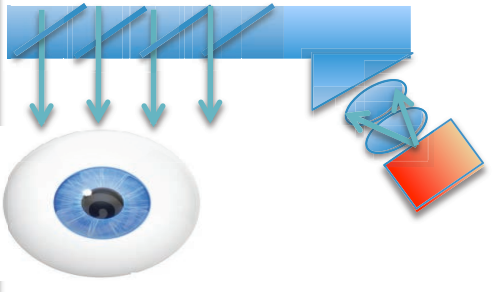
Epson Corp, Moverio (first and second generations)
3 collimation lenses, prism injector, 6 TIR bounces and curved 50/50 mirror
Conventional optics (linear mirror in first gen and curved mirror in second gen)

slide by Bernard Kress



Micro-prism combiner

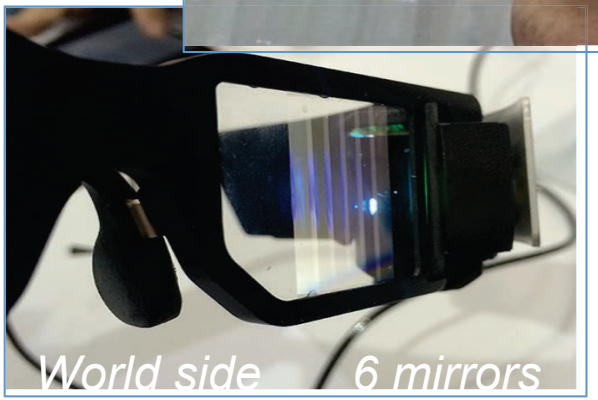
Optinvent Sarl	See through OK Medium FOV Large eyebox Injection molded

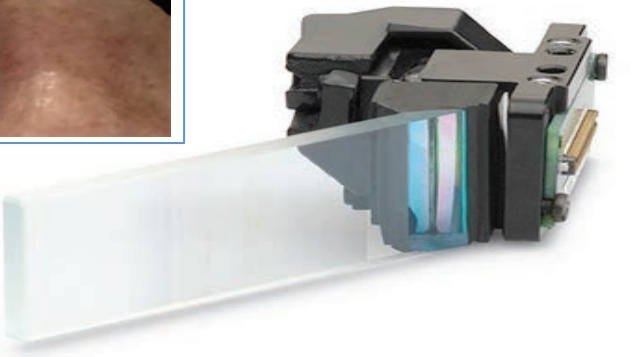


Cascaded coated mirrors combiner

Lumus Ltd	See through OK Medium FOV Large eyebox All glass various coatings

slide by Bernard Kress



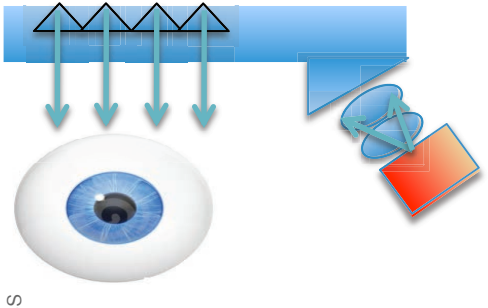


Lumus Ltd, DK32 (40deg FOV, 1.7mm) and DK40 (25 deg FOV. 2.0mm) (cascaded mirrors extractors)

Uses side collimator and prism coupler

slide by Bernard Kress

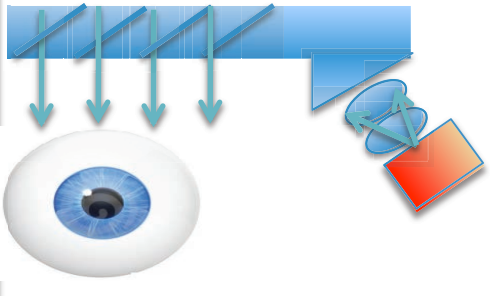
Opaque | Bird bath | Free space | Lightguide | Waveguide EPE



Micro-prism combiner

Optinvent Sarl

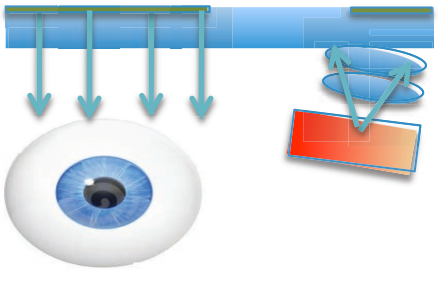
See through OK
Medium FOV
Large eyebox
Injection molded



Cascaded coated mirrors combiner

Lumus Ltd

See through OK
Medium FOV
Large eyebox
All glass
various coatings

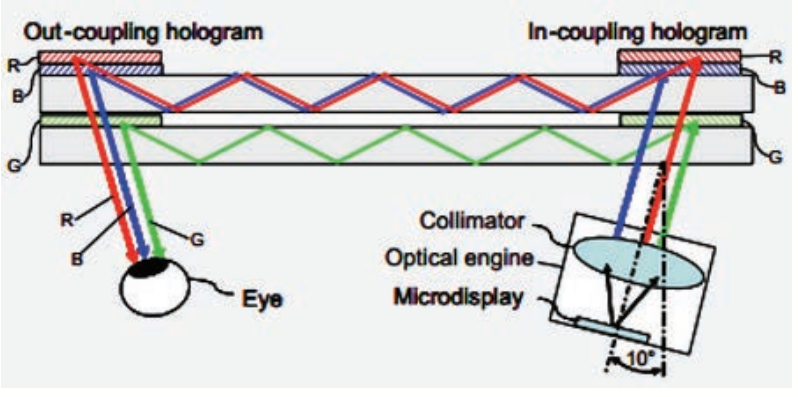


Volume holographic combiner
Diffractive combiner

Sony Ltd
Vuzix /Nokia (M2000AR)
BAE Q-sight

Good see through
Medium FOV
Large eyebox
Photopolymer

slide by Bernard Kress

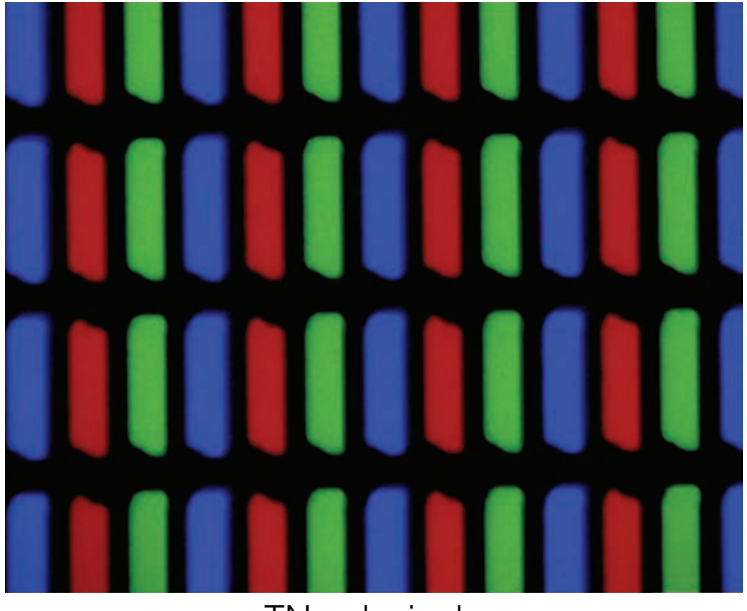


H. Mukawa et al. A full color eyewear display using holographic planar waveguides. Proc. SID 2008.

Microdisplays

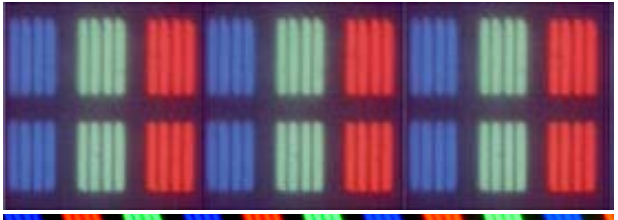
Liquid Crystal Display (LCD) - Subpixels

wikipedia

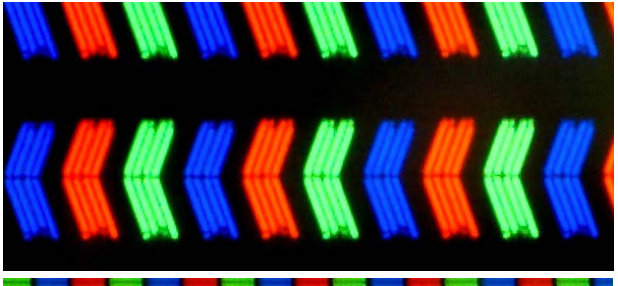


TN subpixels

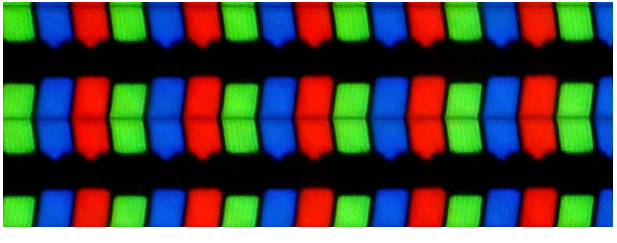
IPS

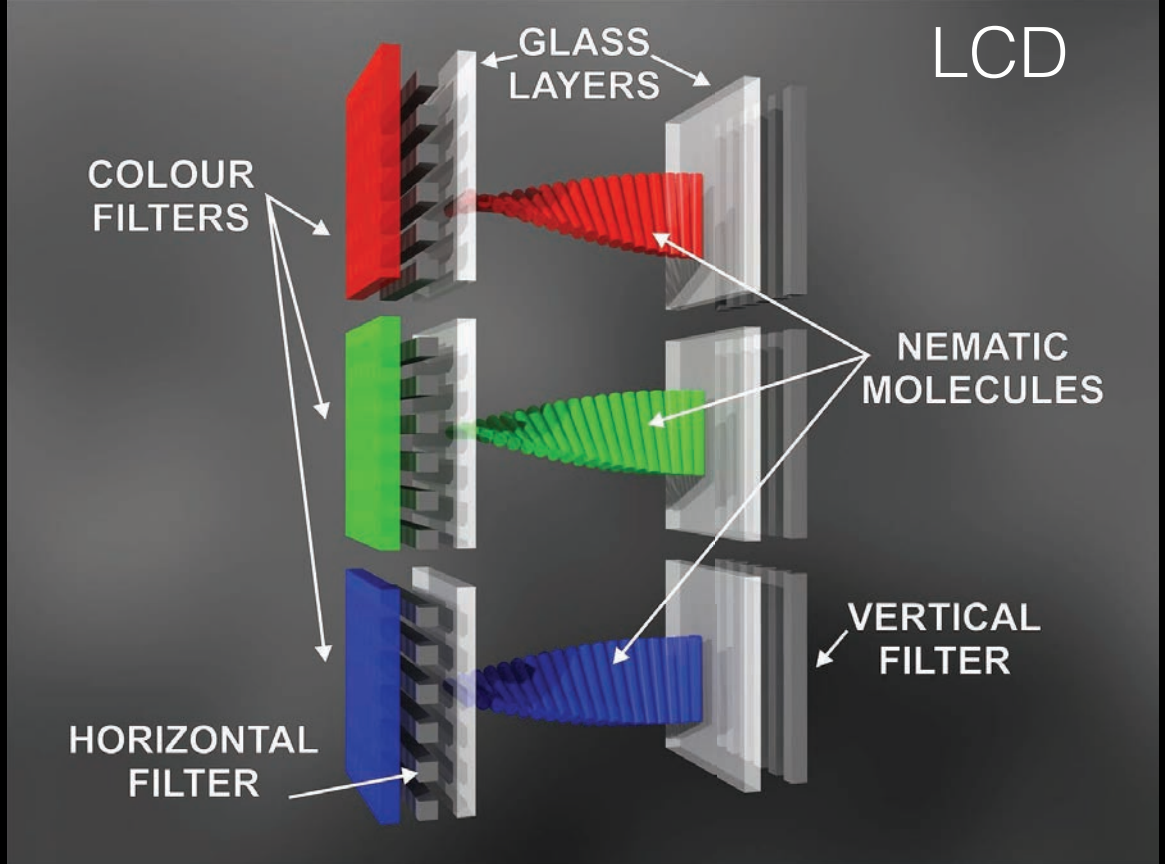


S-IPS



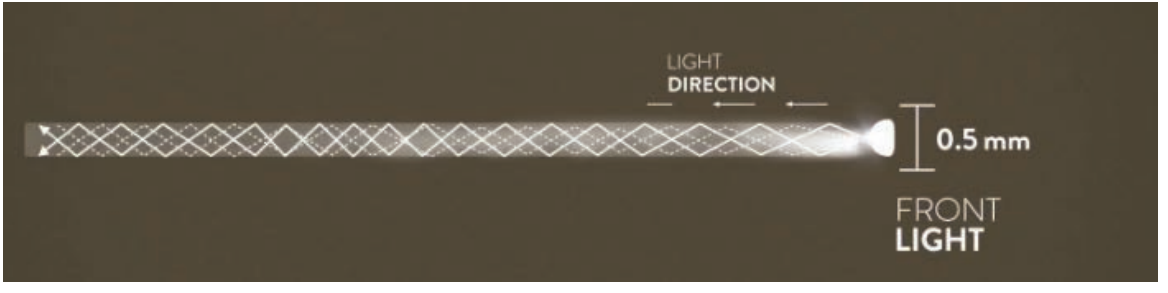
IPS



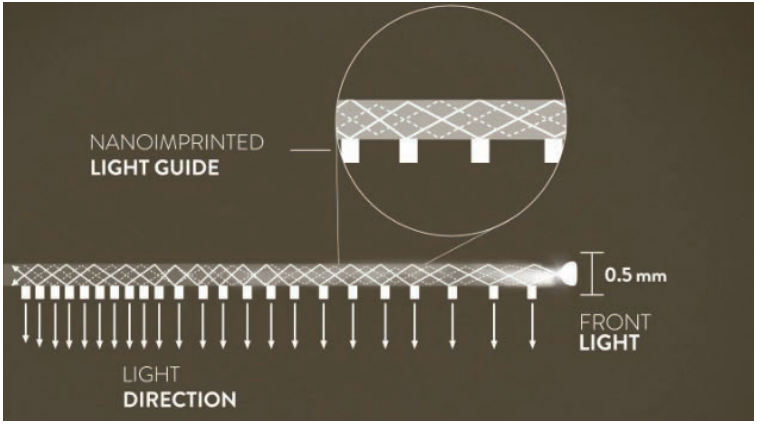

LCD
GLASS LAYERS
COLOUR FILTERS
NEMATIC MOLECULES
VERTICAL FILTER
HORIZONTAL FILTER

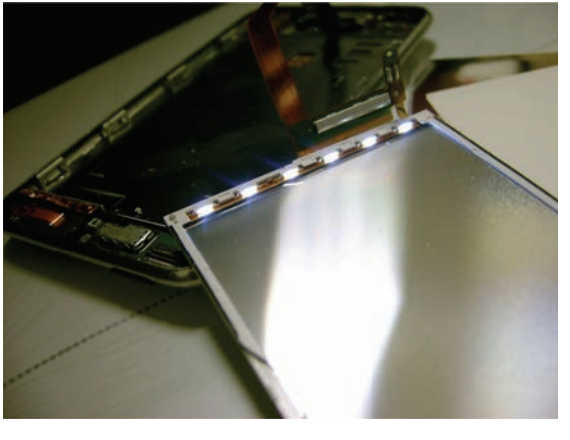
wikipedia

LCD Backlight



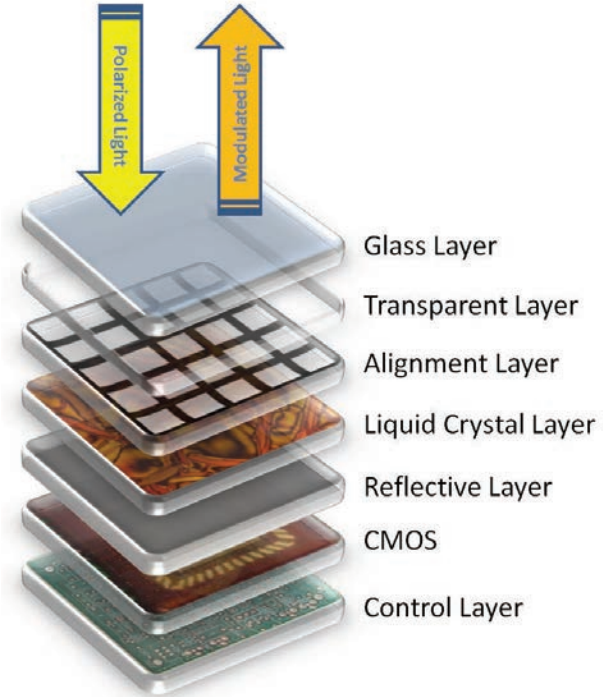
extremetech.com





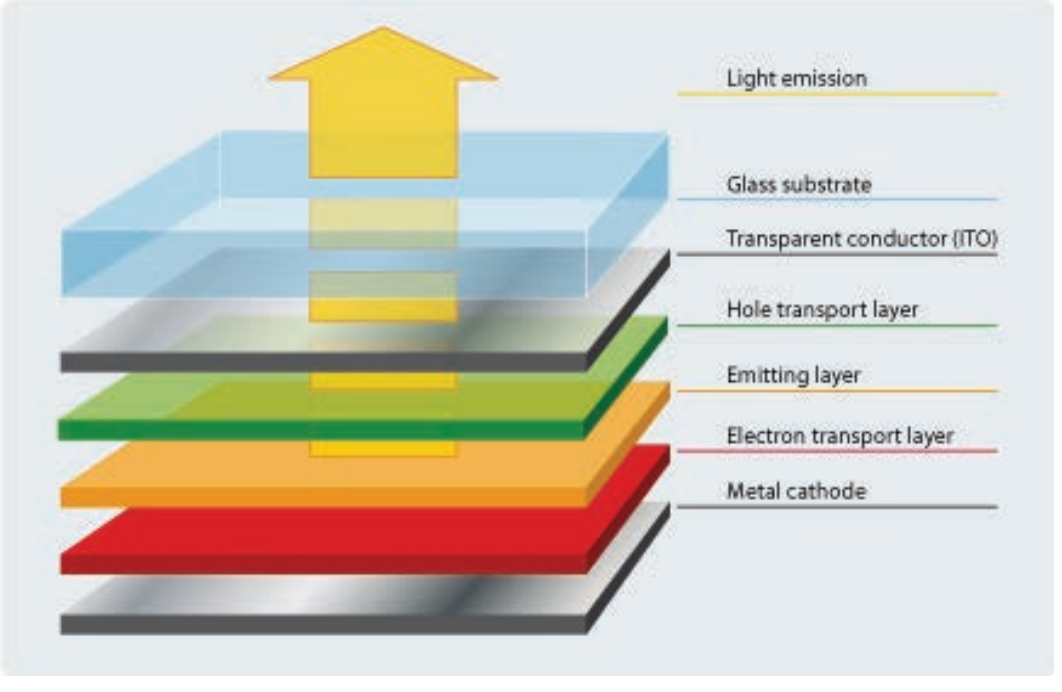
wikipedia

Liquid Crystal on Silicon (LCoS)



- basically a reflective LCD
- standard component in projectors and head mounted displays
- used e.g. in google glass

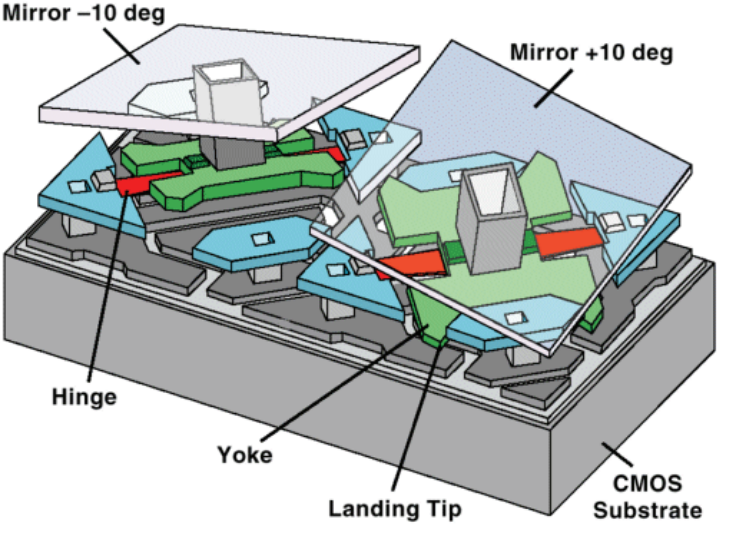
Organic Light Emitting Diodes (OLED)



lightrabbit.co.uk

Digital Micromirror Device (DMD)

- developed by Texas Instruments
- MEMS device
- binary states (e.g. +/- 10 degrees)
- gray-level through pulse width modulation (PWM)



Texas Instruments

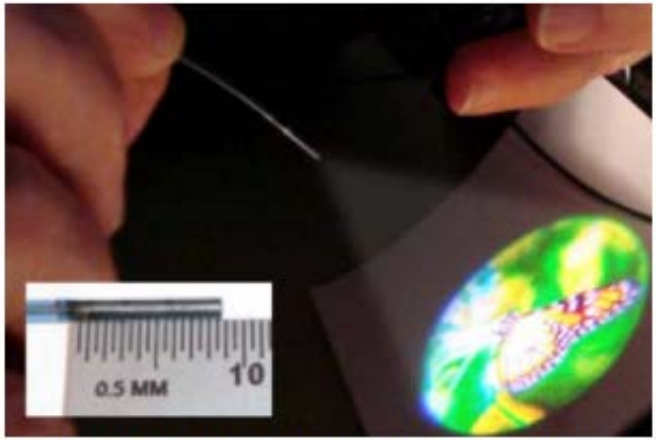
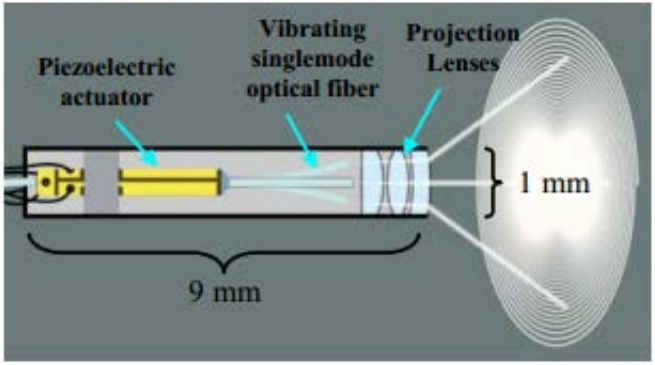


Figure 1. 1 mm x 9 mm scanning fiber projector.



B. T. Schowengerdt, R. Johnston, C.D. Melville, E.J. Seibel. 3D Displays Using Scanning Laser Projection. SID 2012.

Next Lecture: Inertial Measurement Units I

- accelerometers, gyros, magnetometers
- sensor fusion
- head orientation tracking