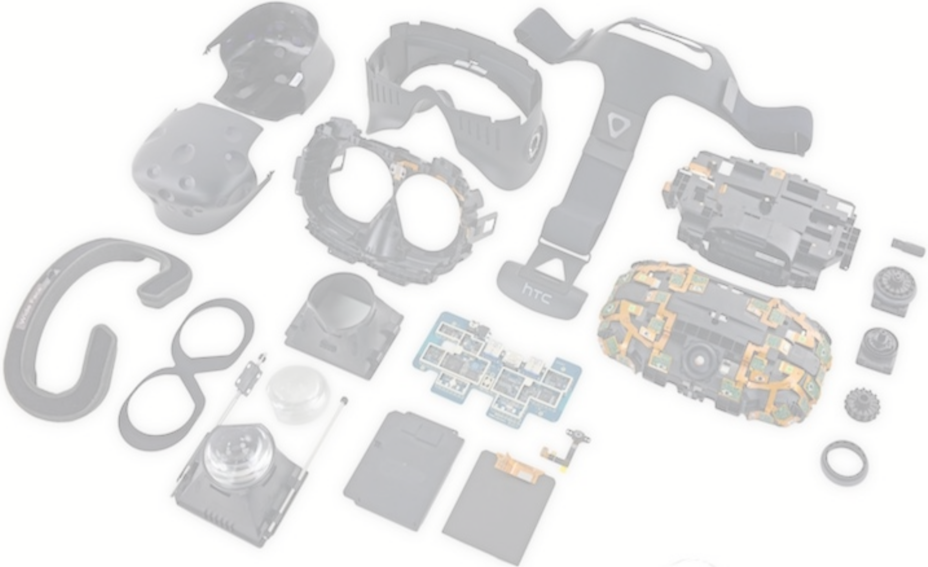
Head Mounted Display Optics II



Gordon Wetzstein
Stanford University

EE 267 Virtual Reality

Lecture 8

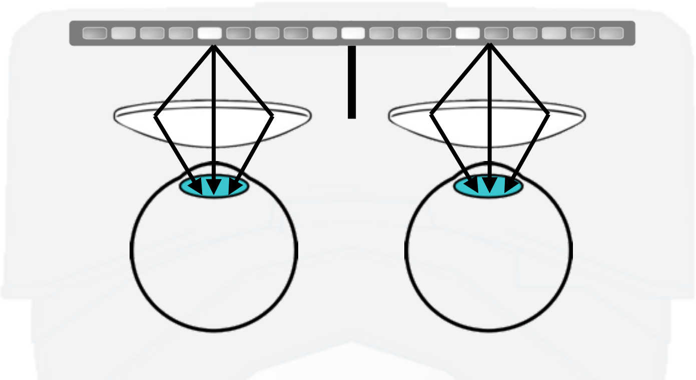
stanford.edu/class/ee267/

Lecture Overview

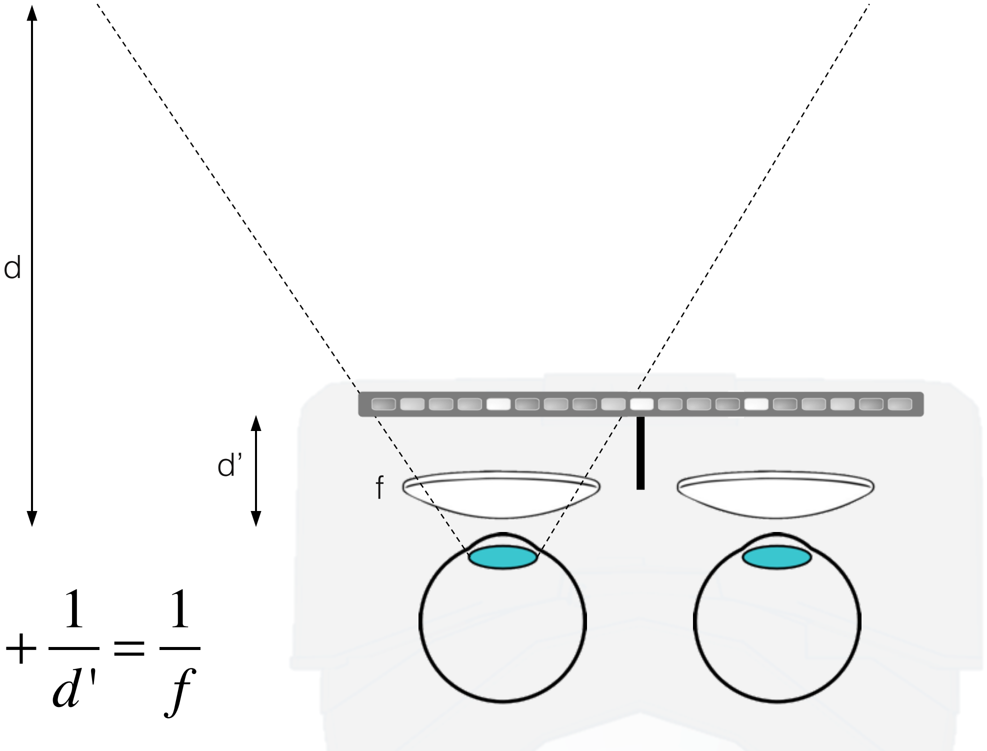
- focus cues & the vergence-accommodation conflict

- advanced optics for VR with focus cues:
    - gaze-contingent varifocal displays
    - volumetric and multi-plane displays
    - near-eye light field displays
    - Maxwellian-type displays

- AR displays



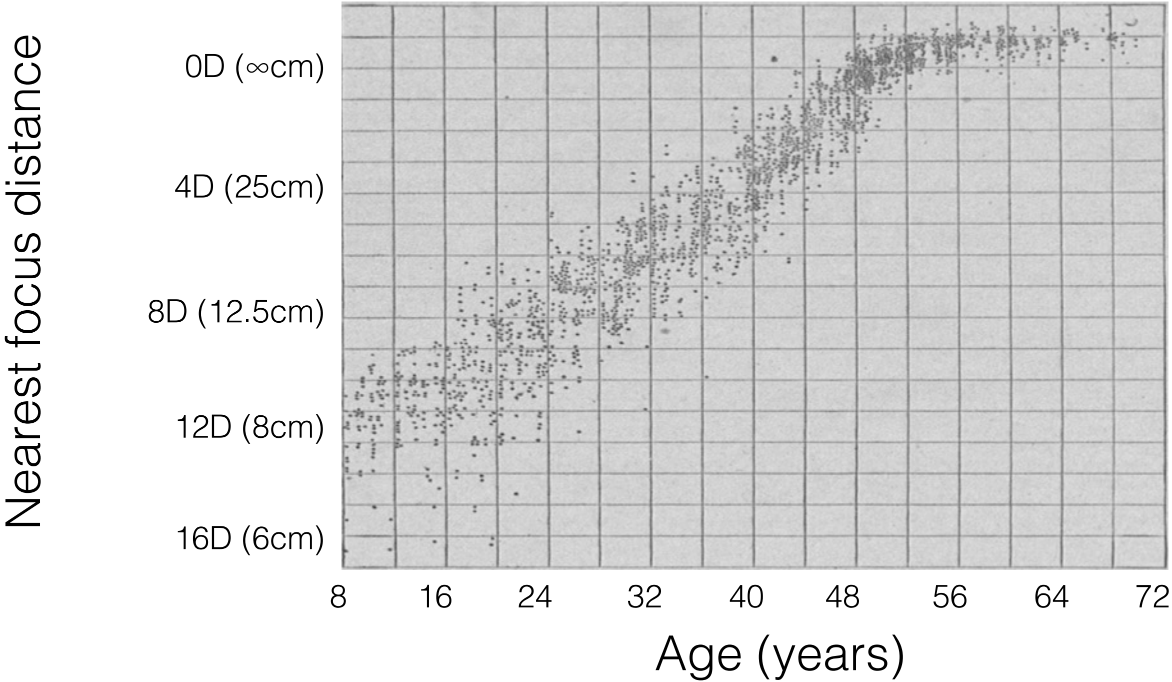
Magnified Display



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

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

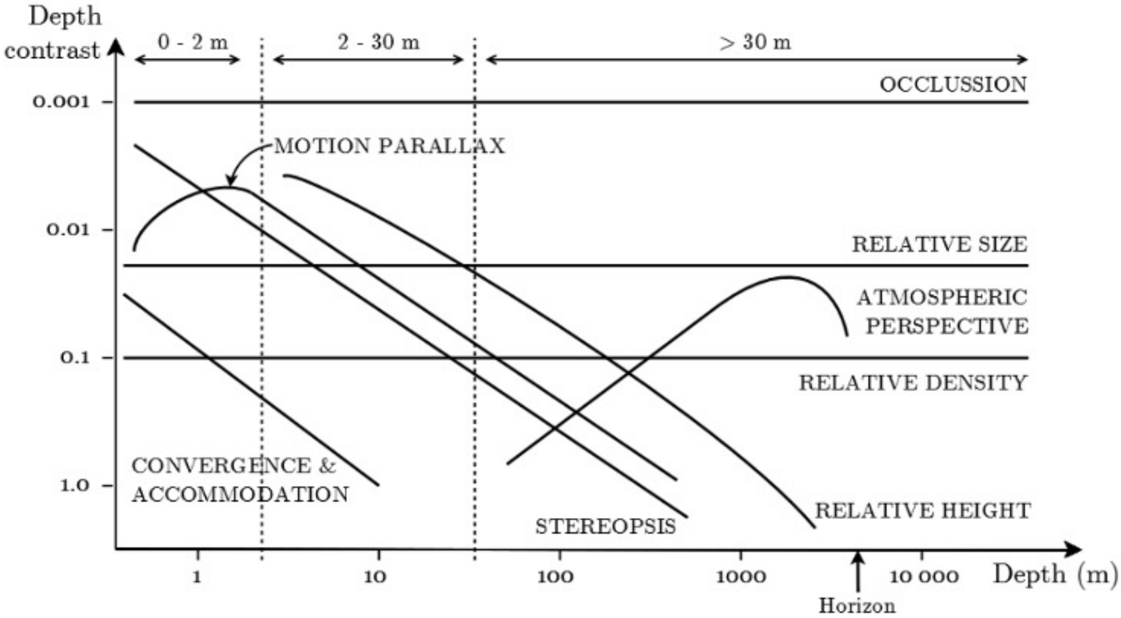
Importance of Focus Cues Decreases with Age - Presbyopia



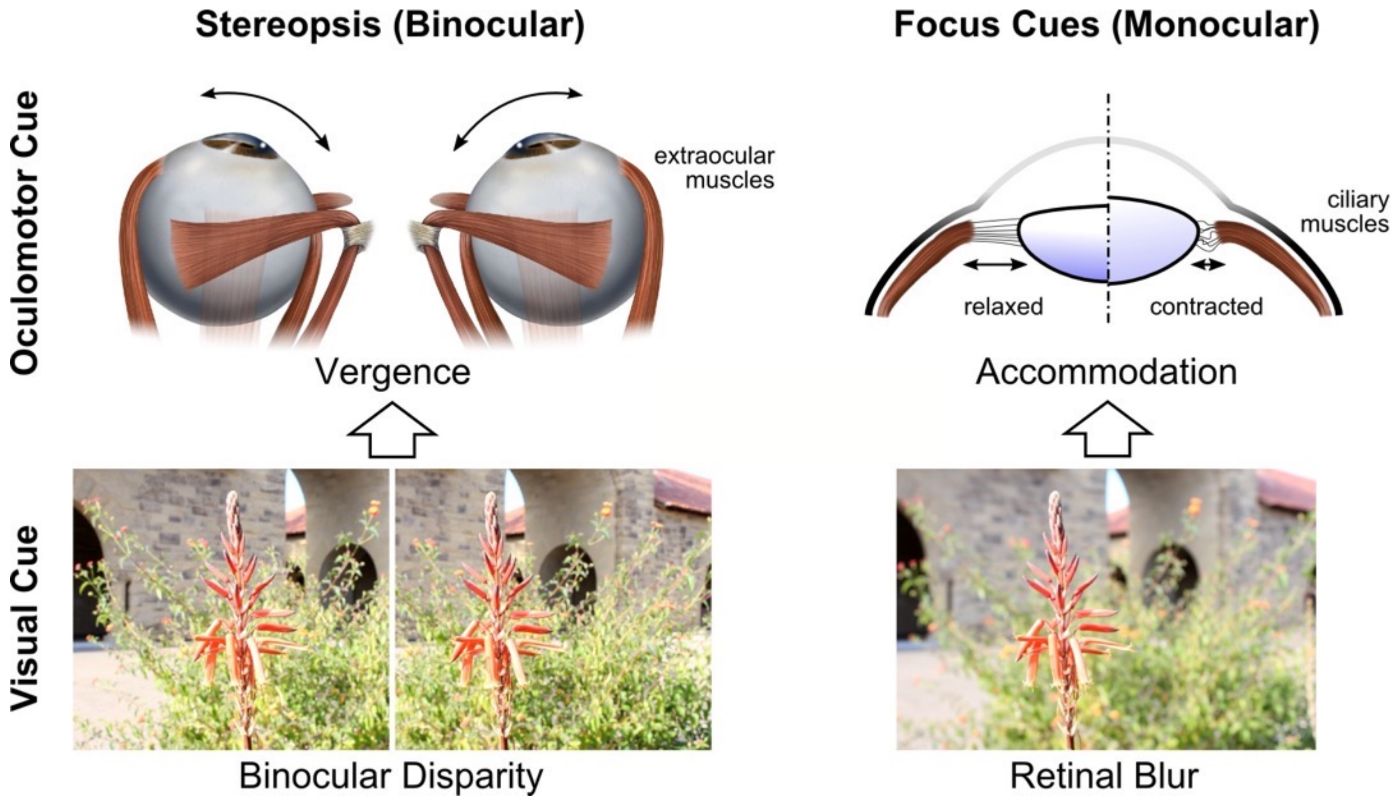
Duane, 1912

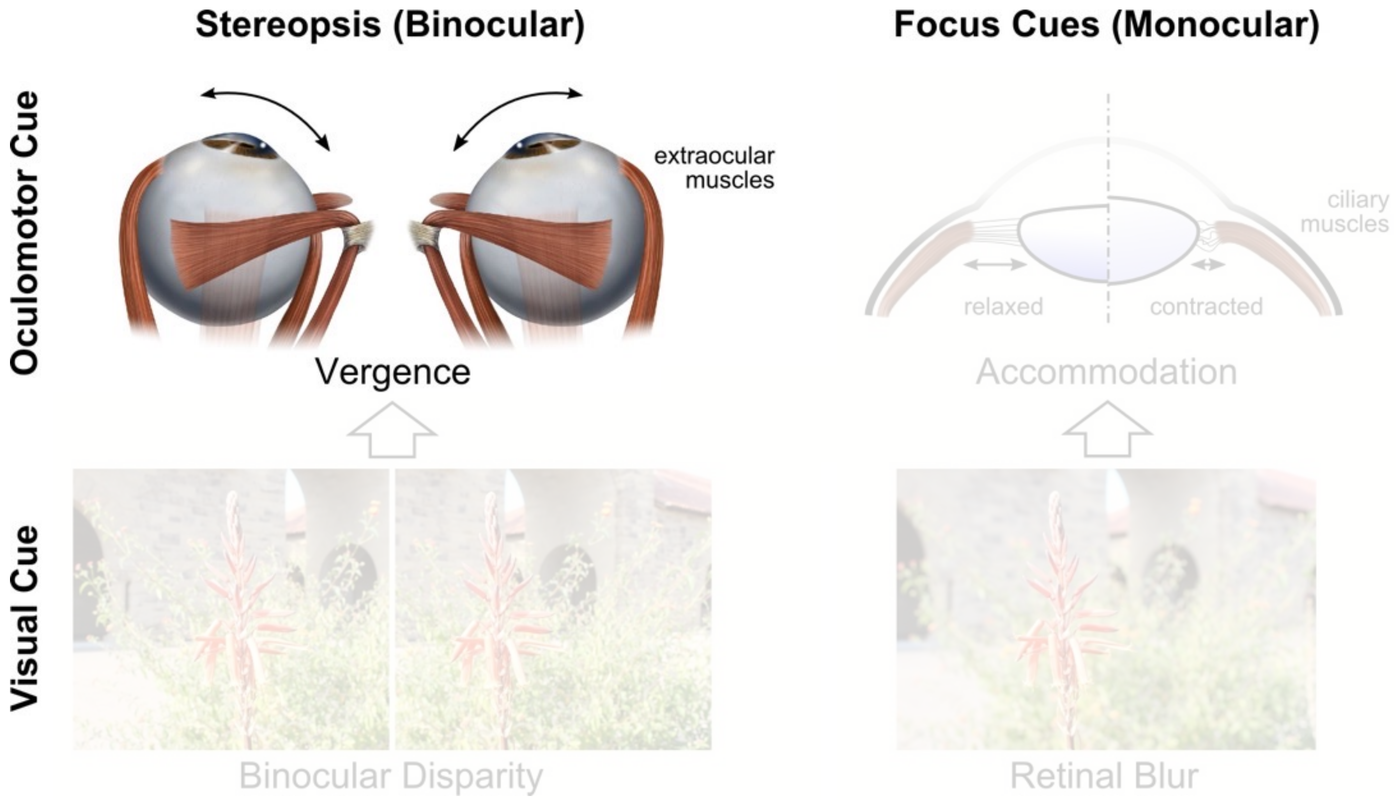
Relative Importance of Depth Cues

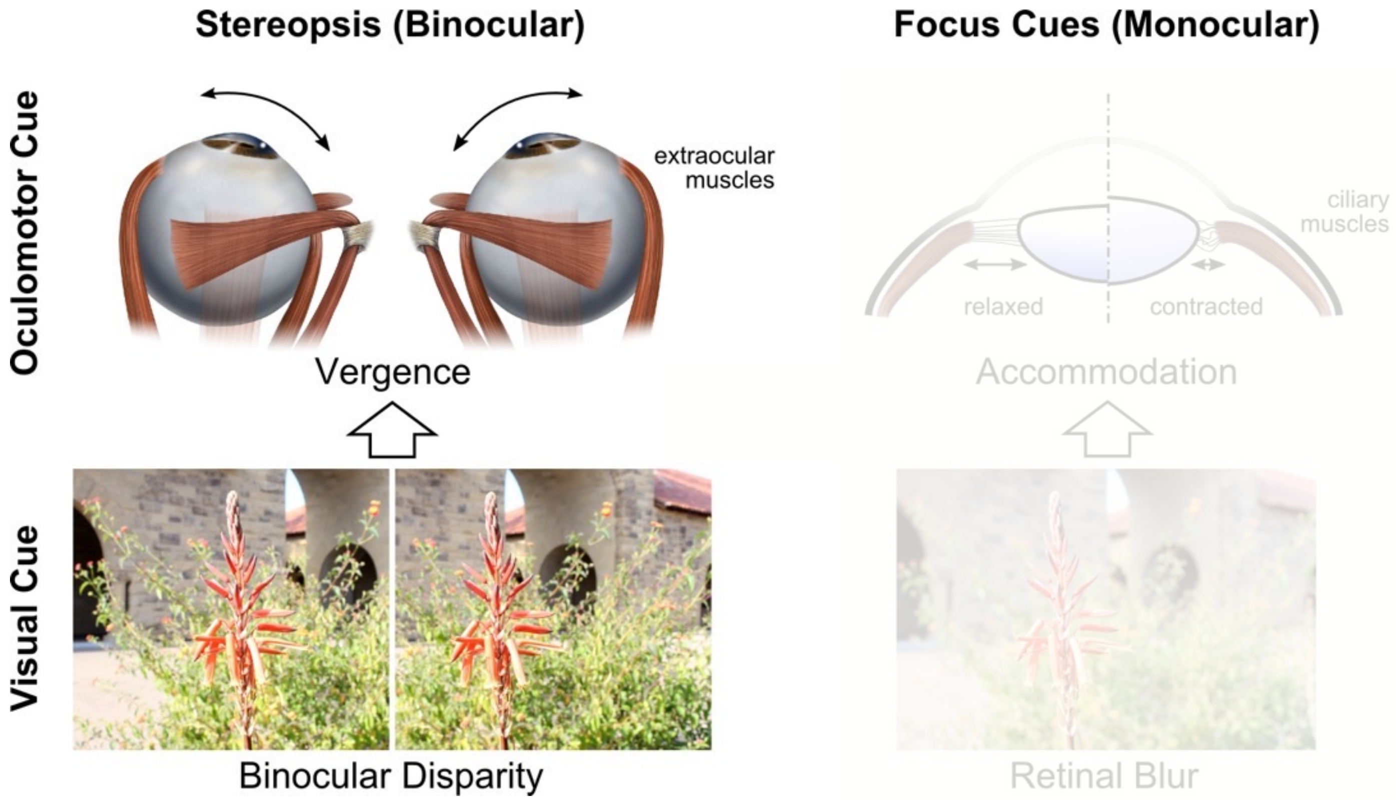
Cutting & Vishton, 1995



The Vergence-Accommodation Conflict (VAC)


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


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



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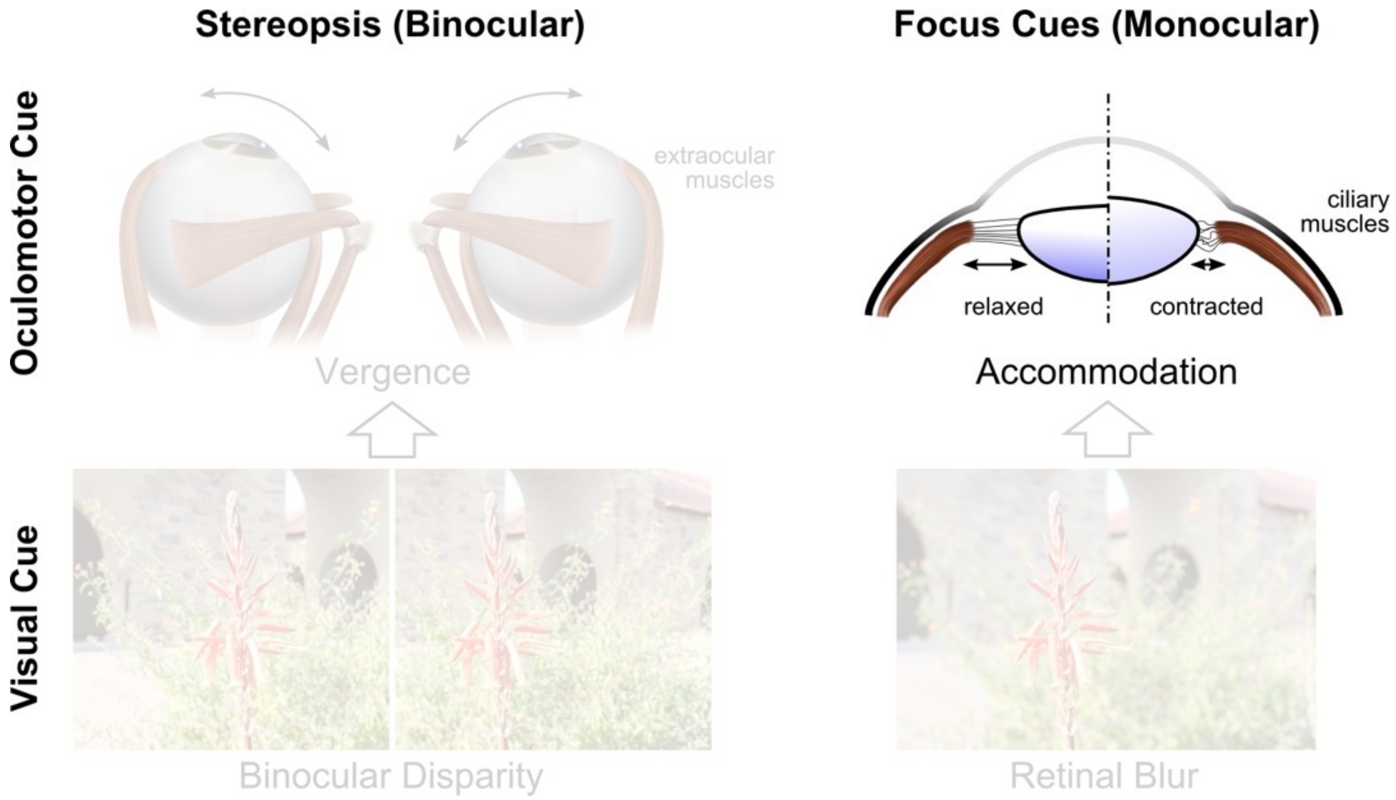
contracted
Vergence
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur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ciliary
muscles
relaxed
contracted
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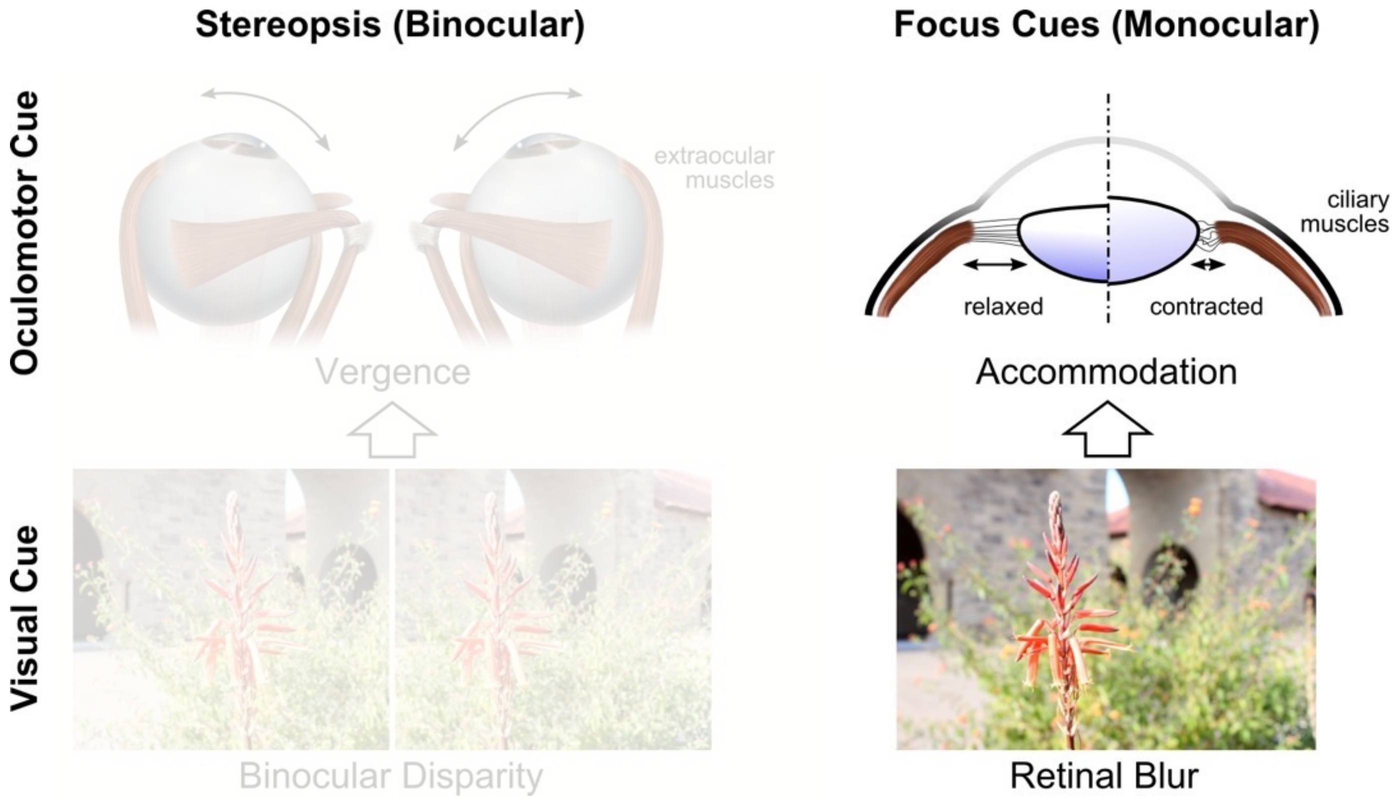
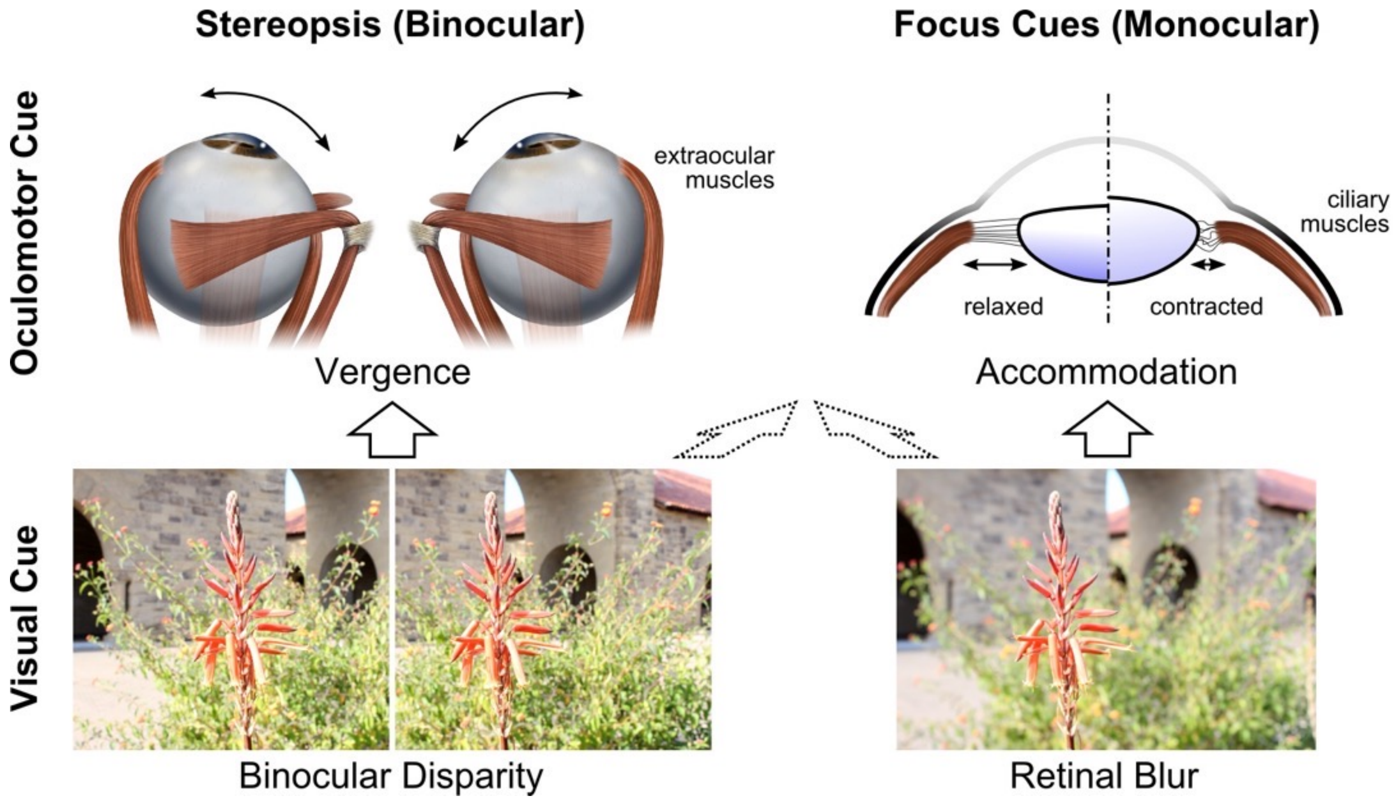
Binocular Disparity
Retinal Blur

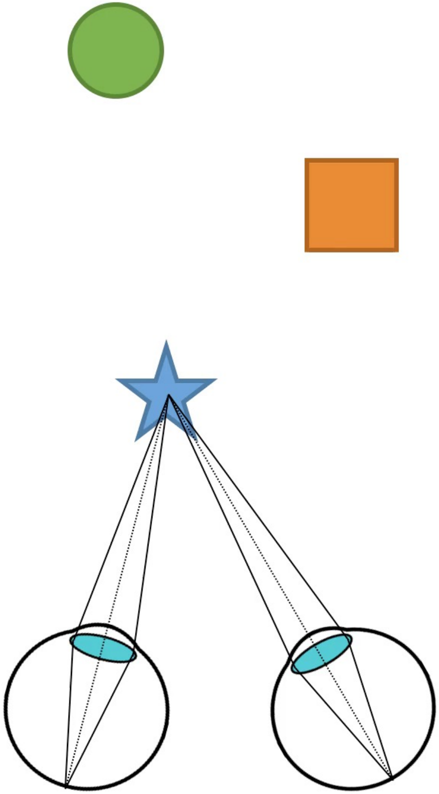


Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
Visual Cue
extraocular muscles
Vergence
ciliary muscles
relaxed
contracted
Accommodation
Binocular Disparity
Retinal Blur

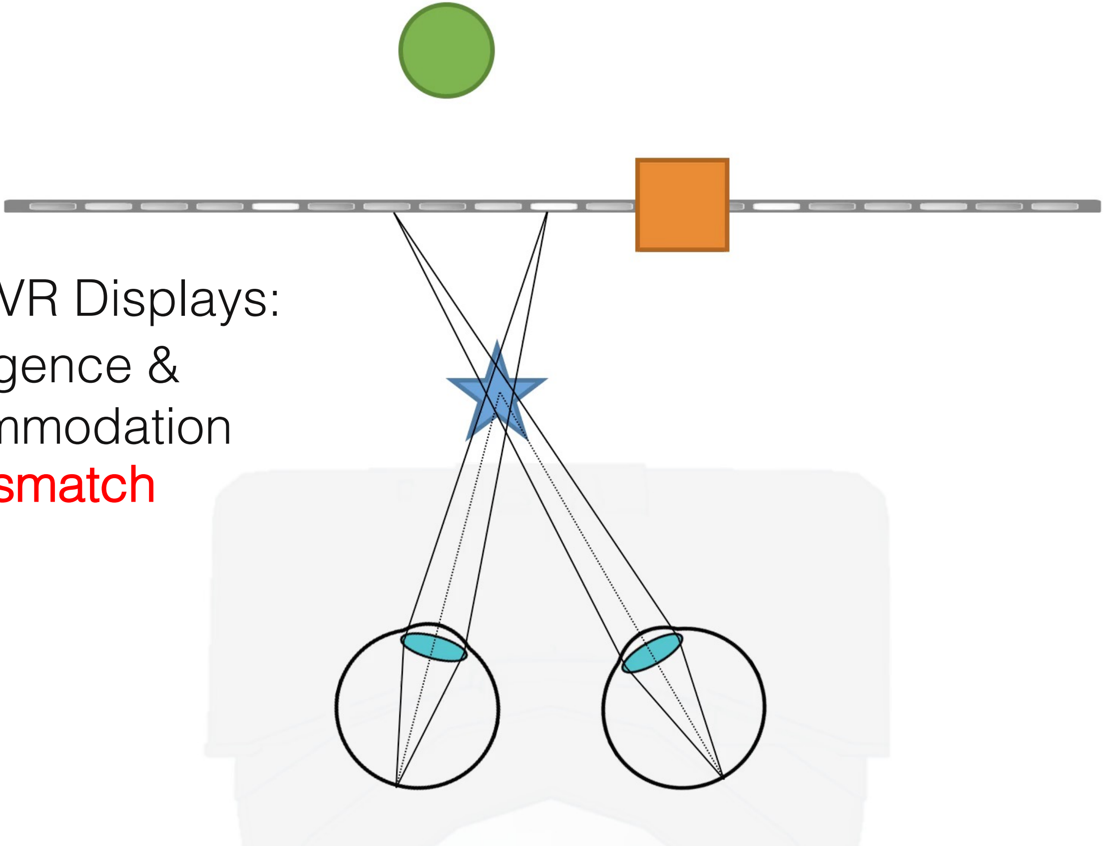


Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
ciliary muscles
relaxed
contracted
Vergence
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur

Real World:
Vergence &
Accommodation
Match!

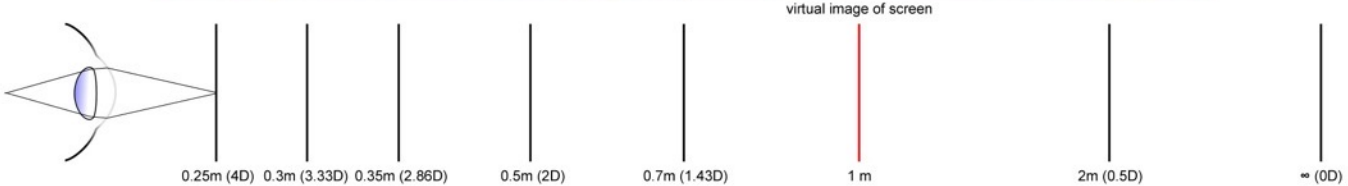


Current VR Displays:
Vergence &
Accommodation
Mismatch



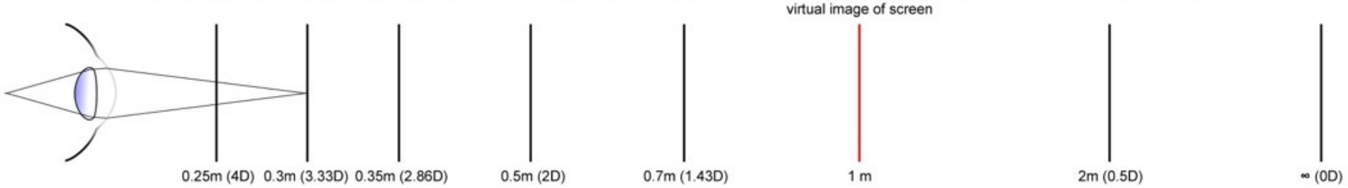
Accommodation and Retinal Blur

Conventional Display



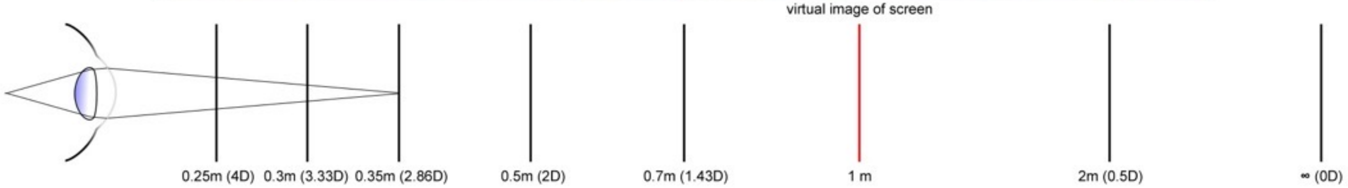
Blur Gradient Driven Accommodation

Conventional Display



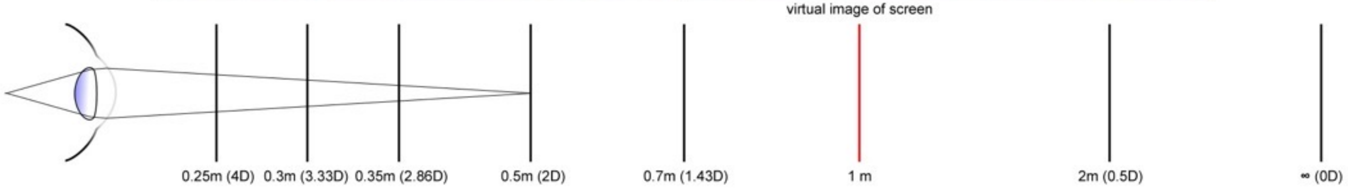
Blur Gradient Driven Accommodation

Conventional Display



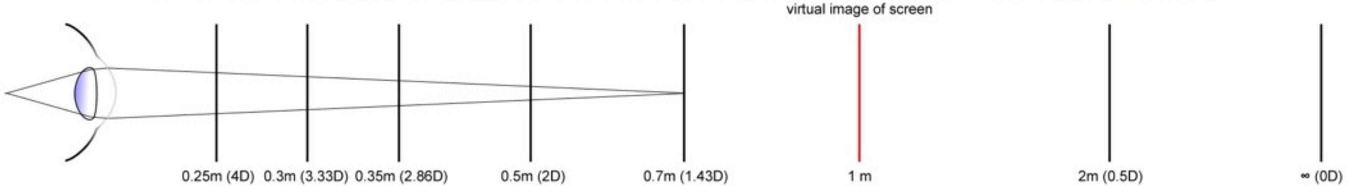
Blur Gradient Driven Accommodation

Conventional Display



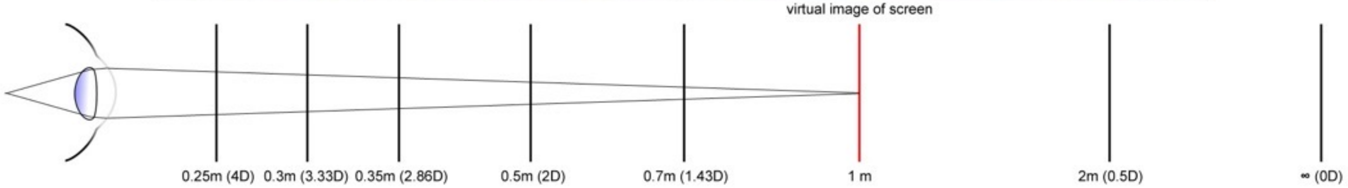
Blur Gradient Driven Accommodation

Conventional Display



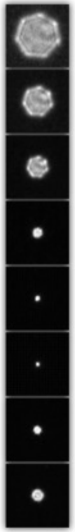
Blur Gradient Driven Accommodation

Conventional Display

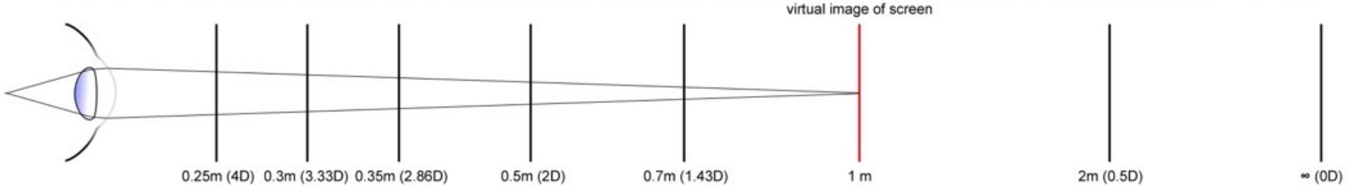


Blur Gradient Driven Accommodation

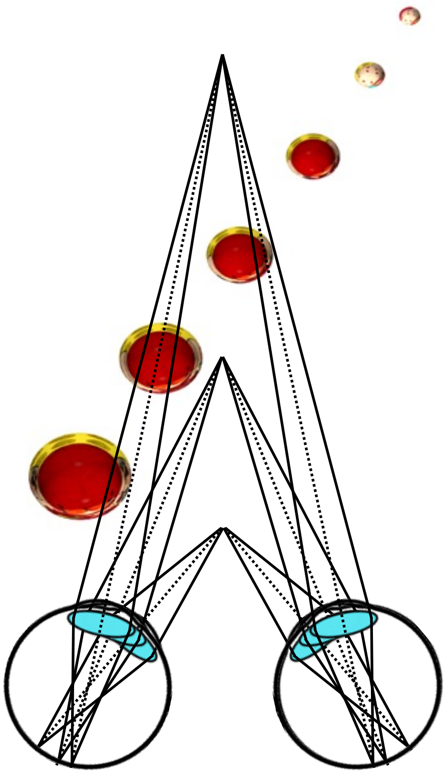
Accommodation-dependent Point Spread Functions



Conventional Display

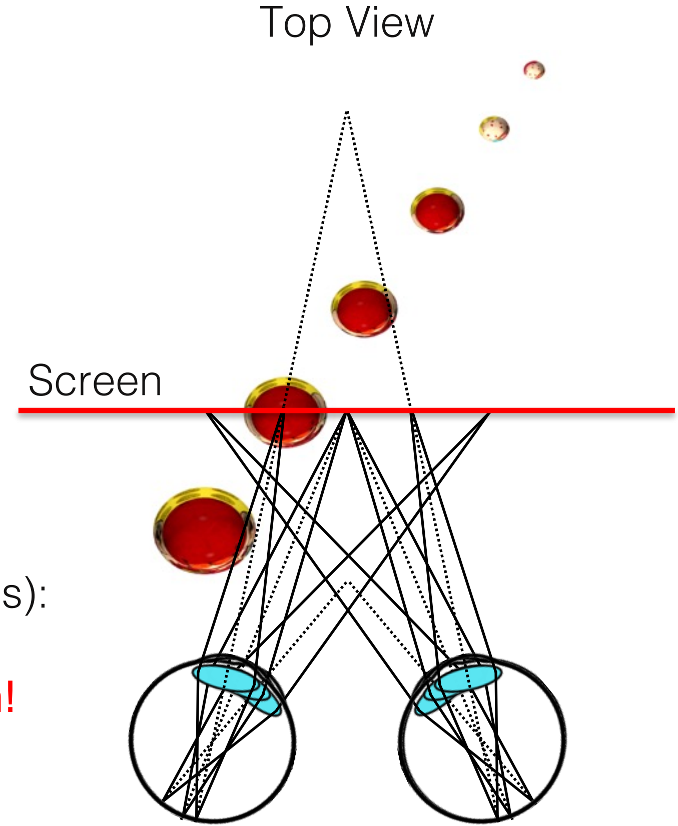


Top View



Real World:

Vergence & Accommodation Match!



Stereo Displays Today (including HMDs):

Vergence-Accommodation Mismatch!

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)

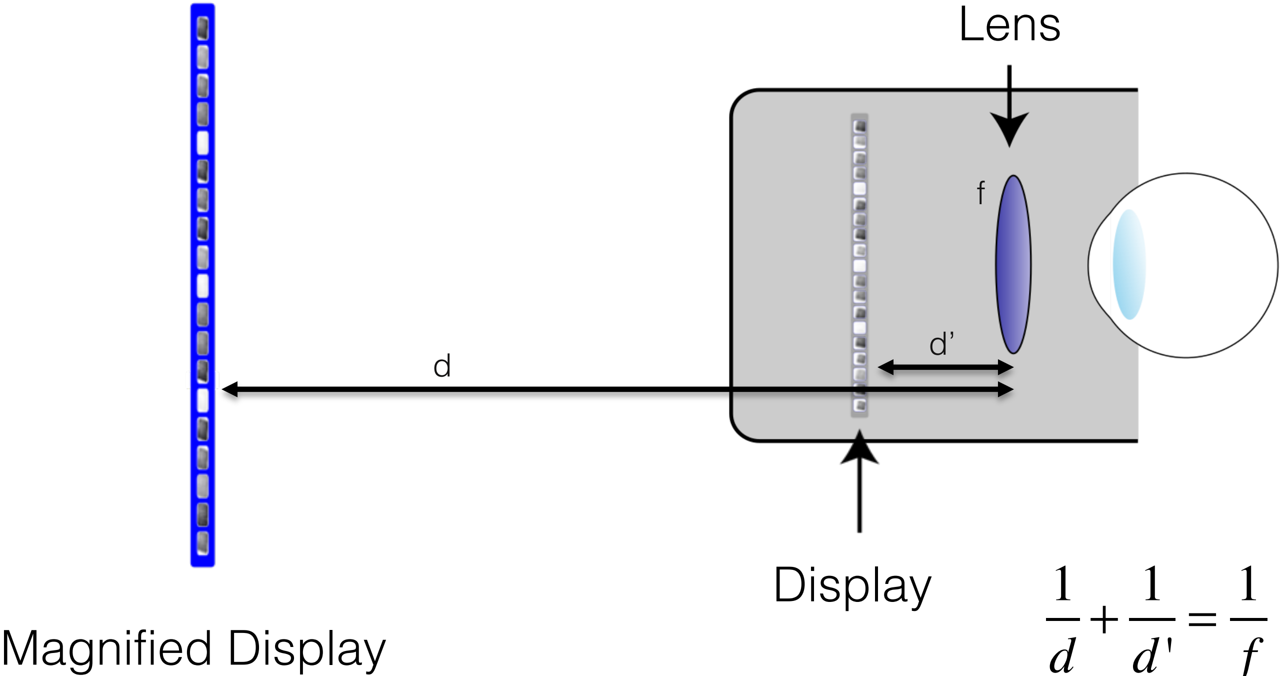
- Degrades visual performance in terms of reaction times and acuity for stereoscopic vision (Hoffman et al. 2008; Konrad et al. 2016; Johnson et al. 2016)

- Short-term effects: *double vision (diplopia), reduced visual clarity*

VR Displays with Focus Cues

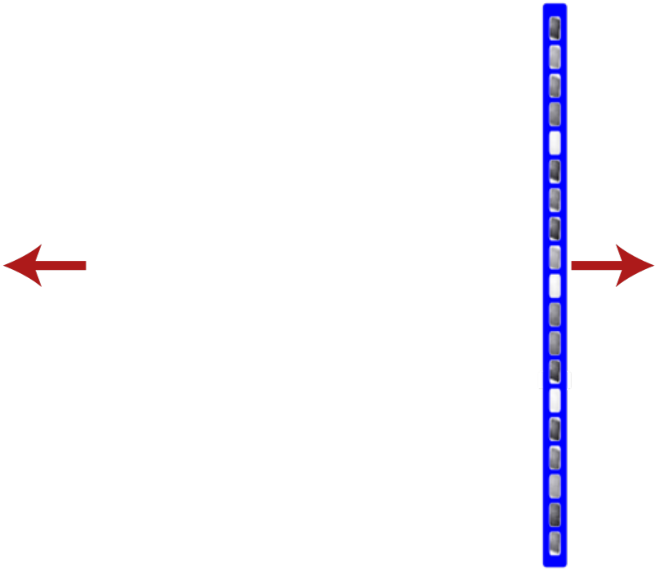
1. Gaze-contingent Varifocal Displays

Fixed Focus Displays



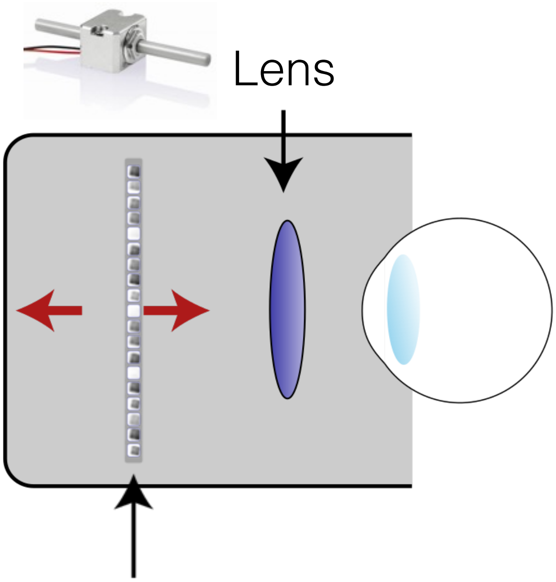
$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{f}$$

Varifocal Displays



Magnified Display

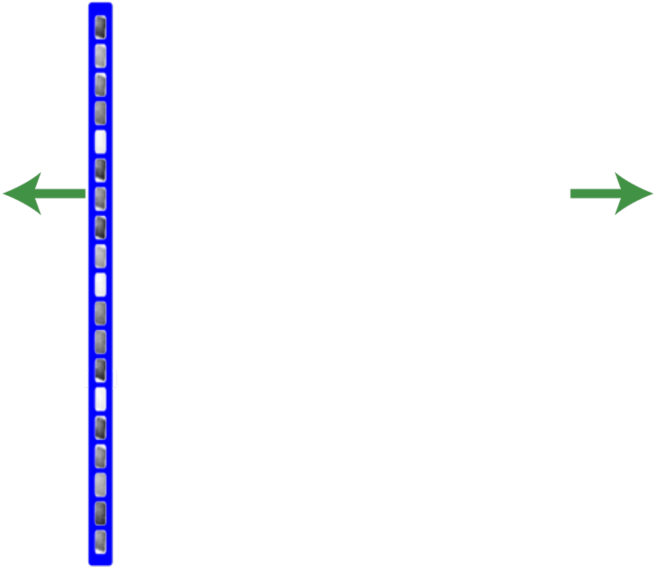
actuator → vary d’



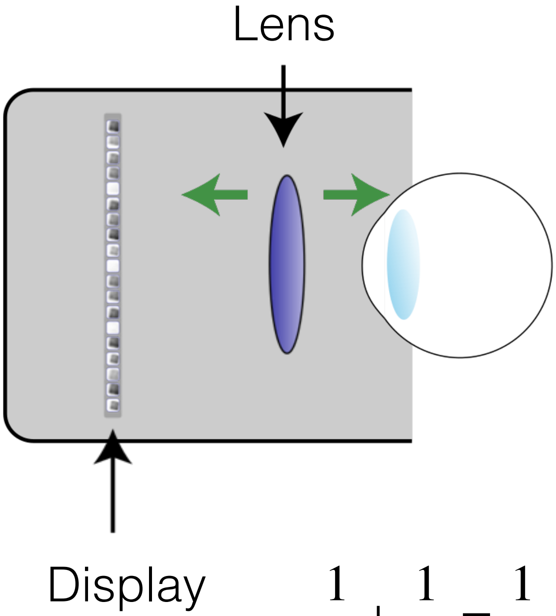
$$\frac{1}{d} + \frac{1}{\boxed{d'}} = \frac{1}{f}$$

Varifocal Displays

focus-tunable lens → vary f

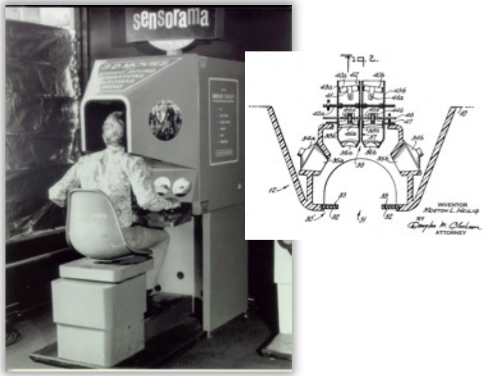


Magnified Display

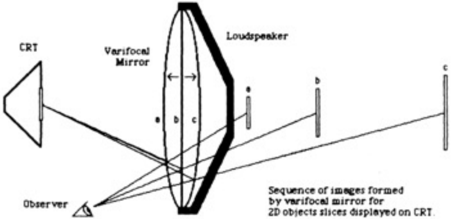


$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{\boxed{f}}$$

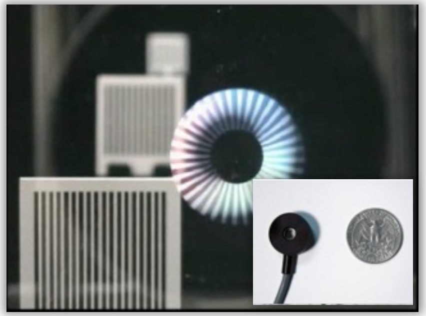
Varifocal Displays - History



manual focus adjustment
Heilig 1962

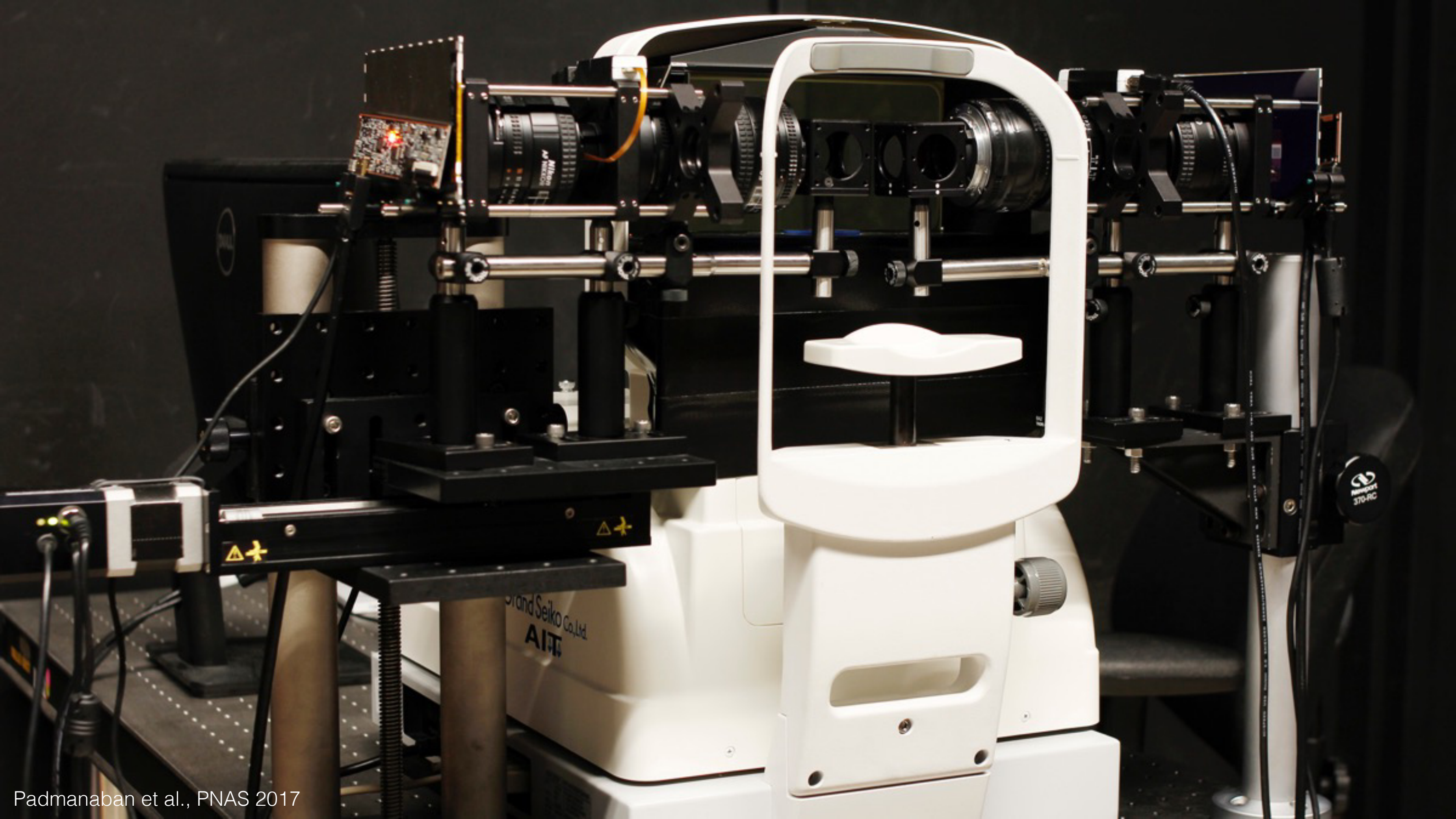


automatic focus adjustment
Mills 1984

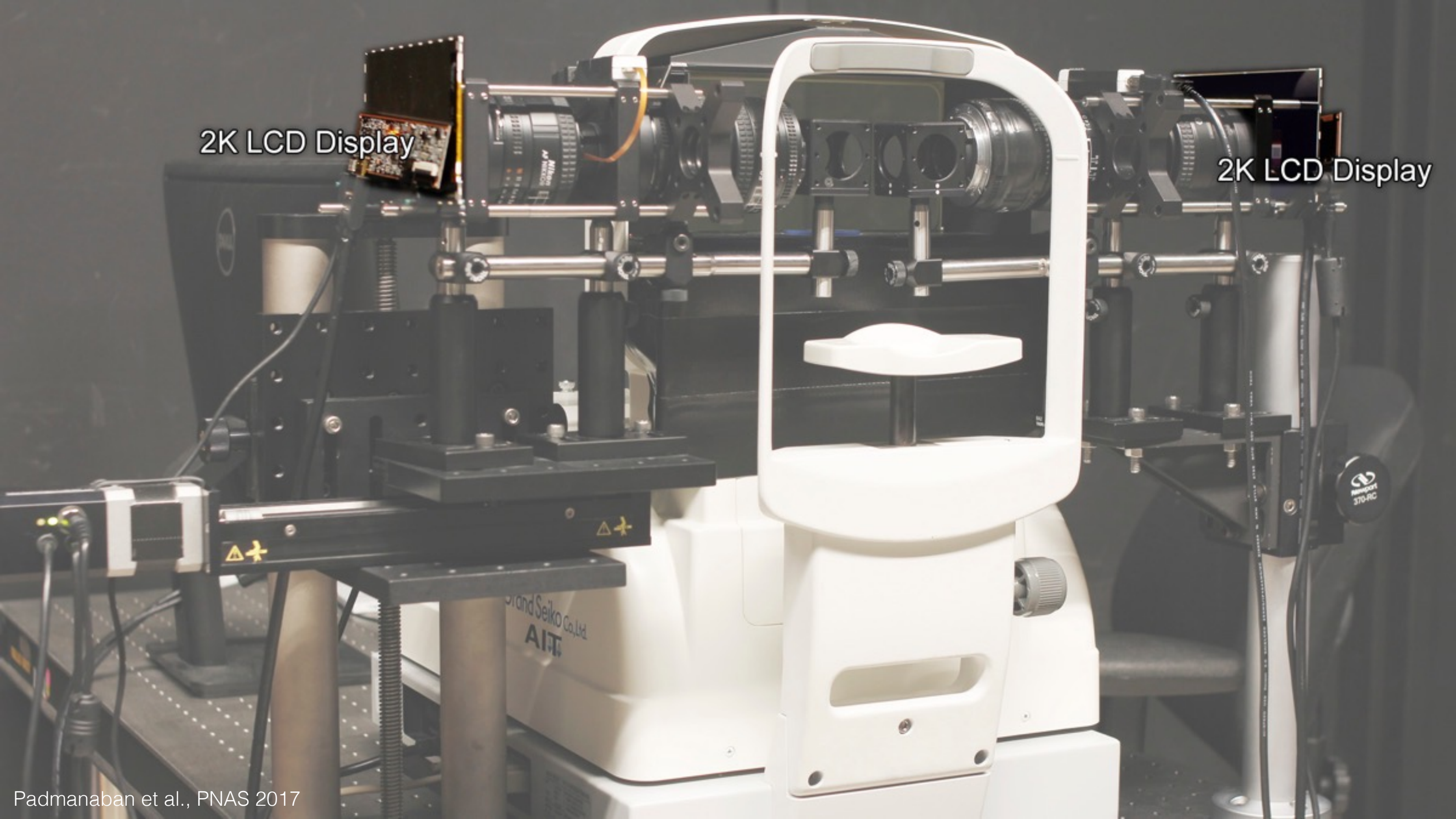


deformabe mirrors & lenses
McQuaide 2003, Liu 2008

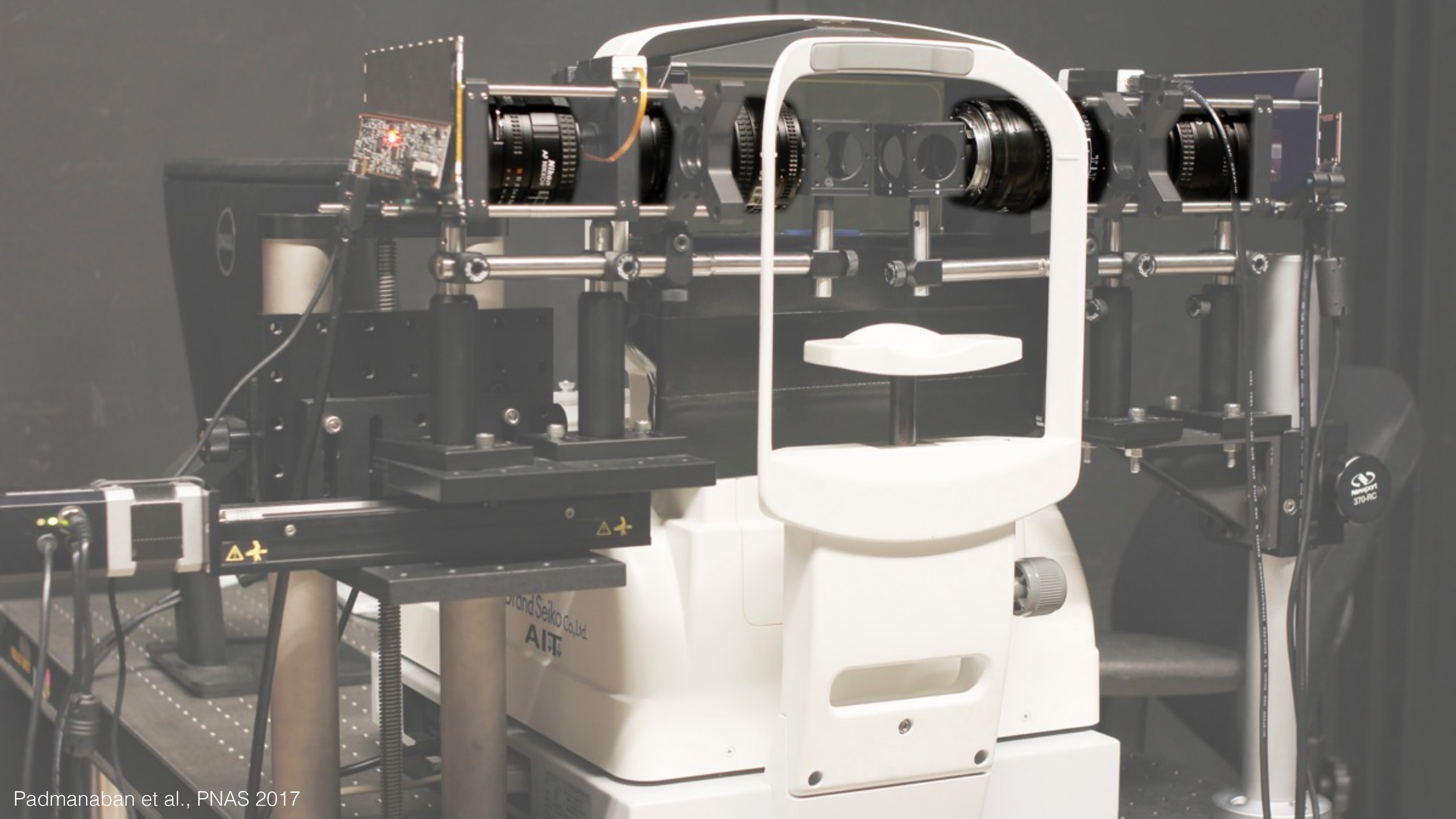
- M. Heilig "Sensorama", 1962 (US Patent #3,050,870)
- P. Mills, H. Fuchs, S. Pizer "High-Speed Interaction On A Vibrating-Mirror 3D Display", SPIE 0507 1984
- S. Shiwa, K. Omura, F. Kishino "Proposal for a 3-D display with accommodative compensation: 3DDAC", JSID 1996
- S. McQuaide, E. Seibel, J. Kelly,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



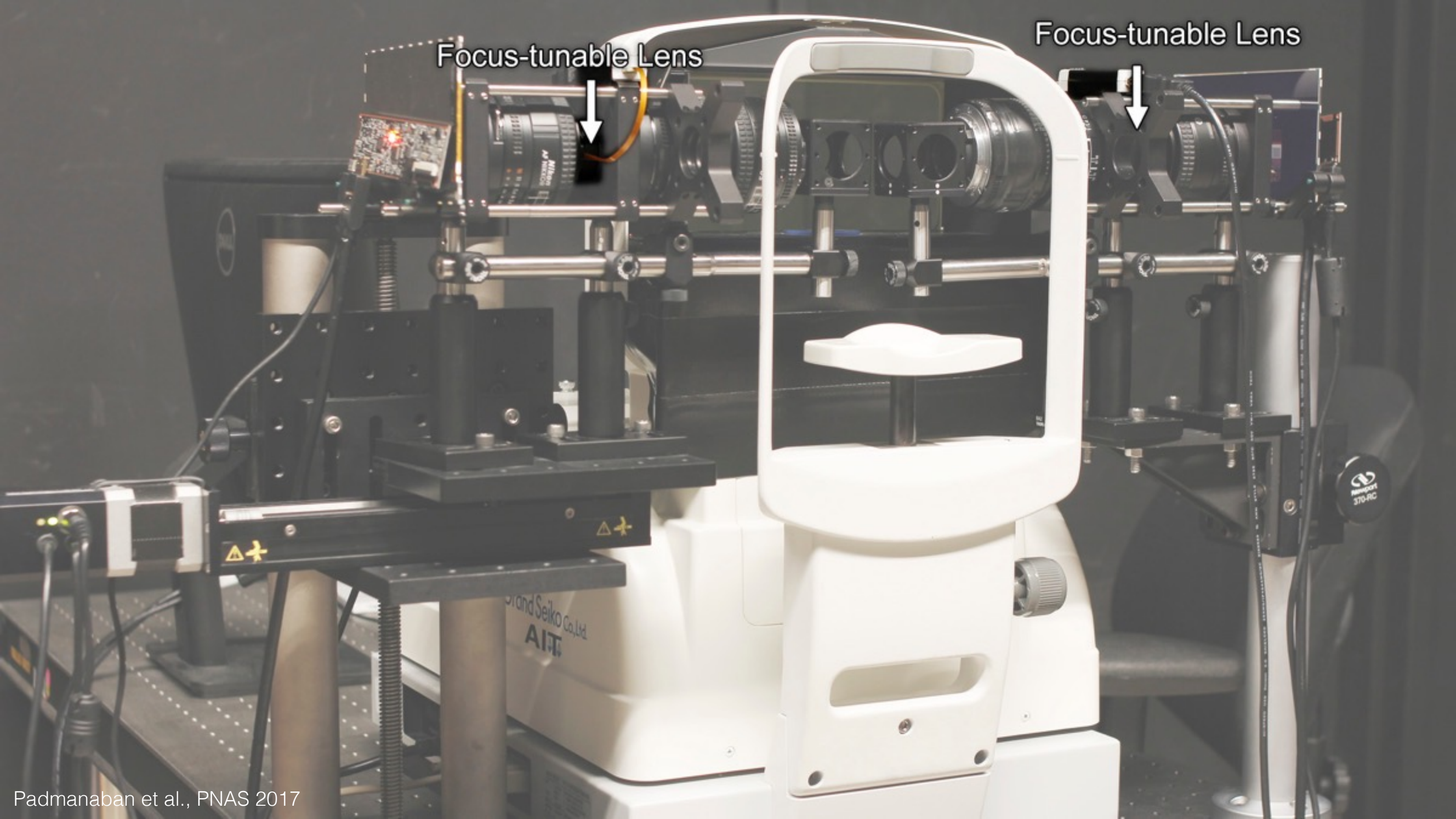
Padmanaban et al., PNAS 2017



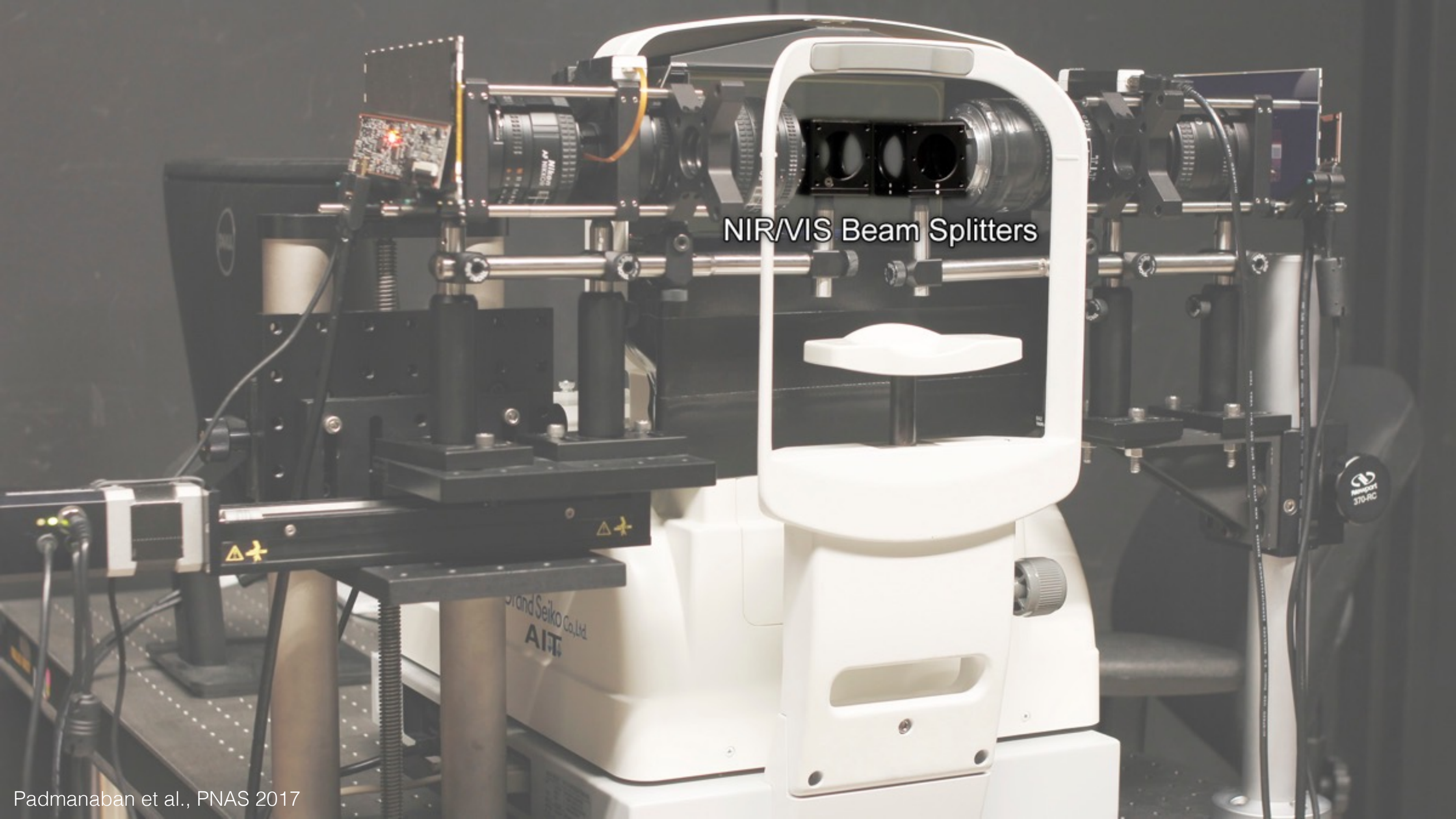
Padmanaban et al., PNAS 2017



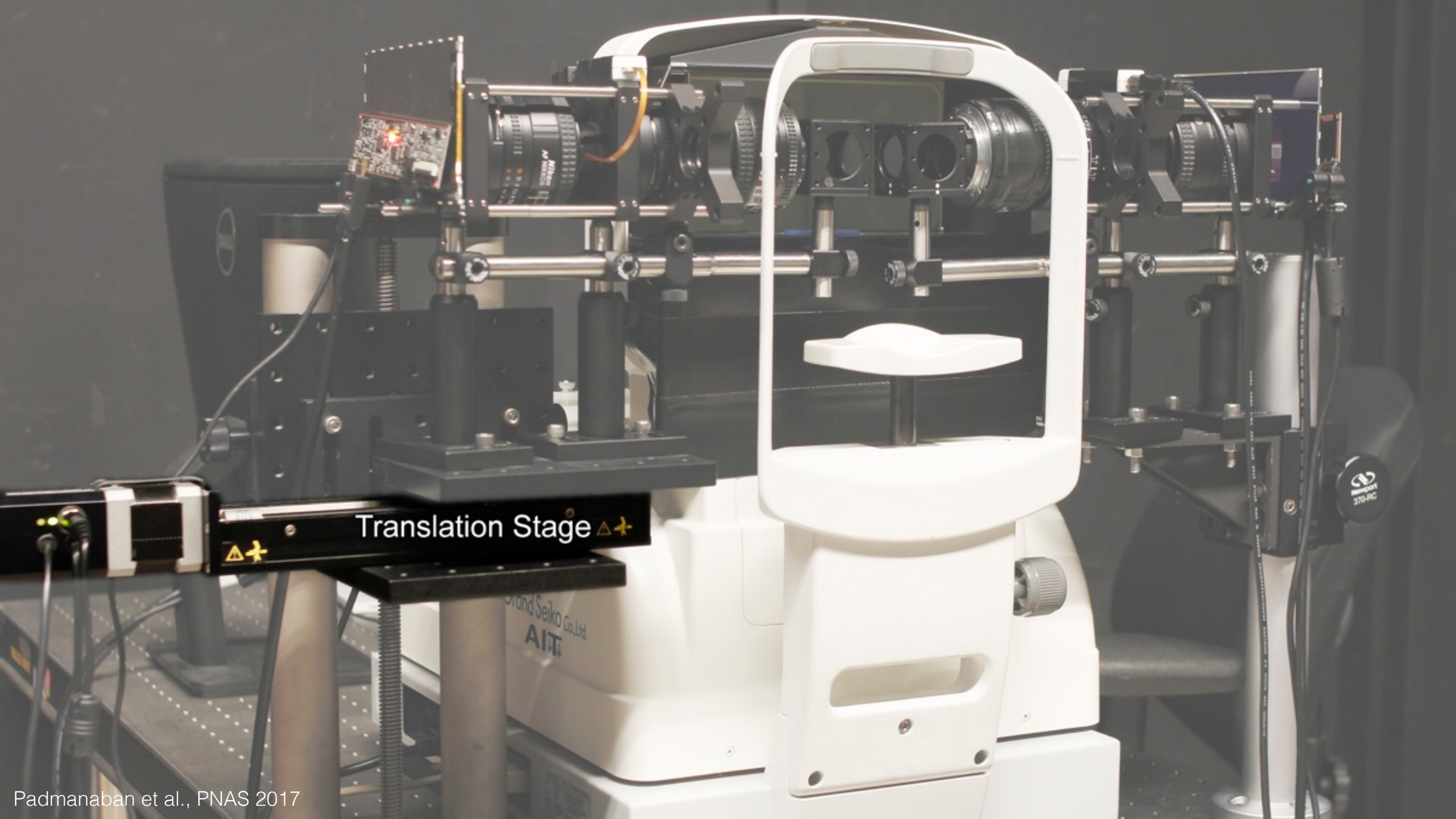
Padmanaban et al., PNAS 2017



Padmanaban et al., PNAS 2017

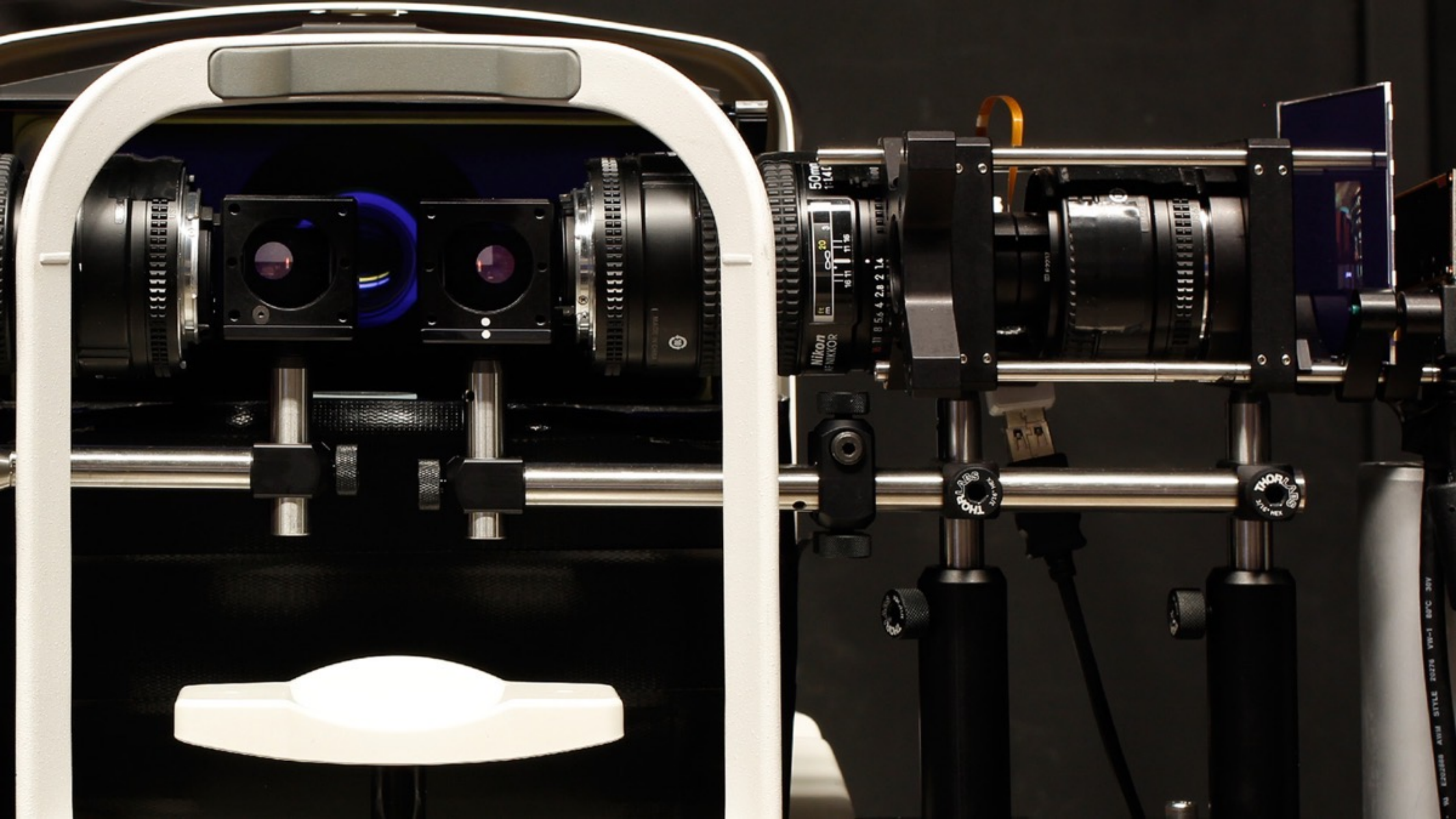


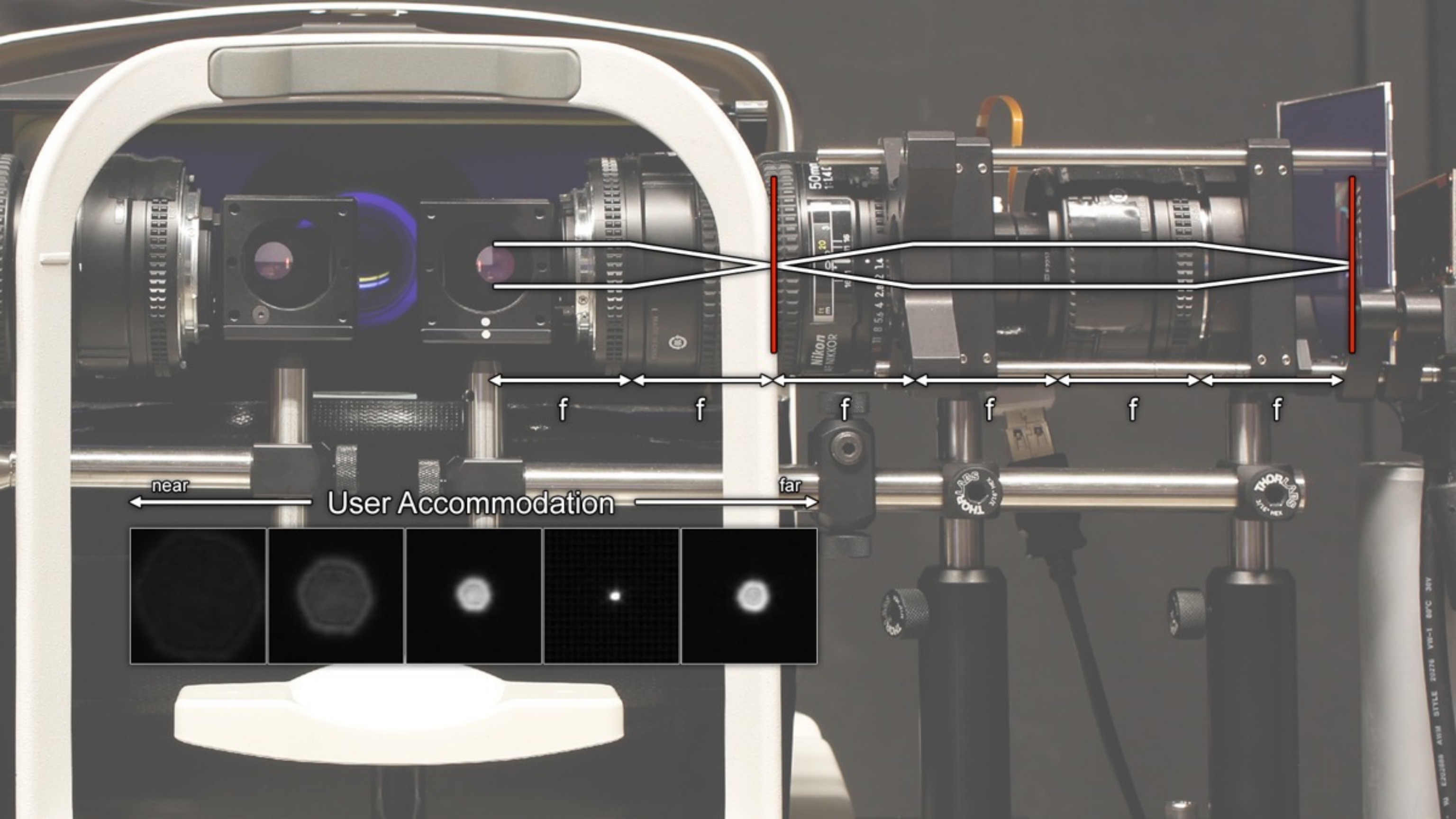
Padmanaban et al., PNAS 2017

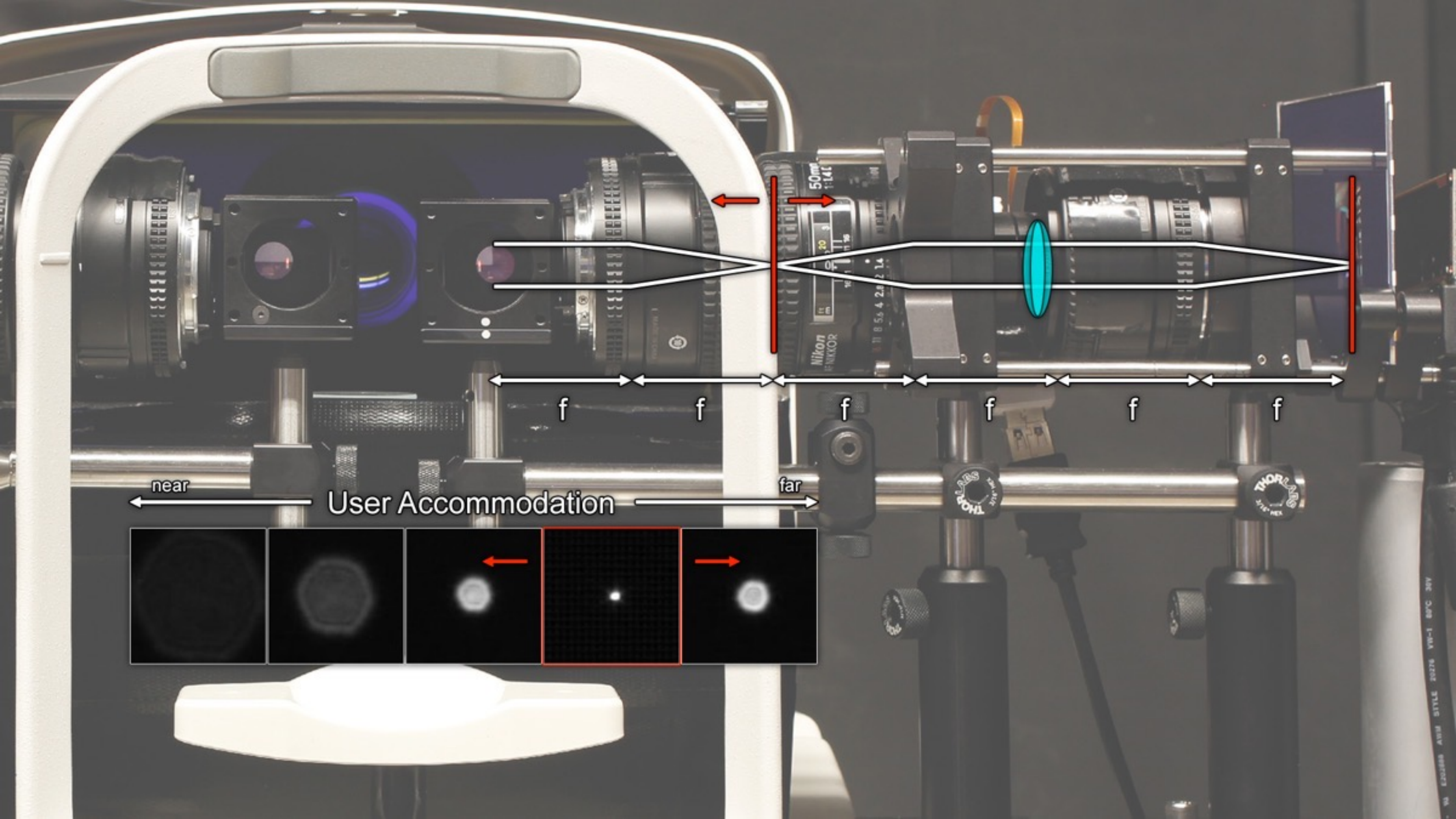


Padmanaban et al., PNAS 2017

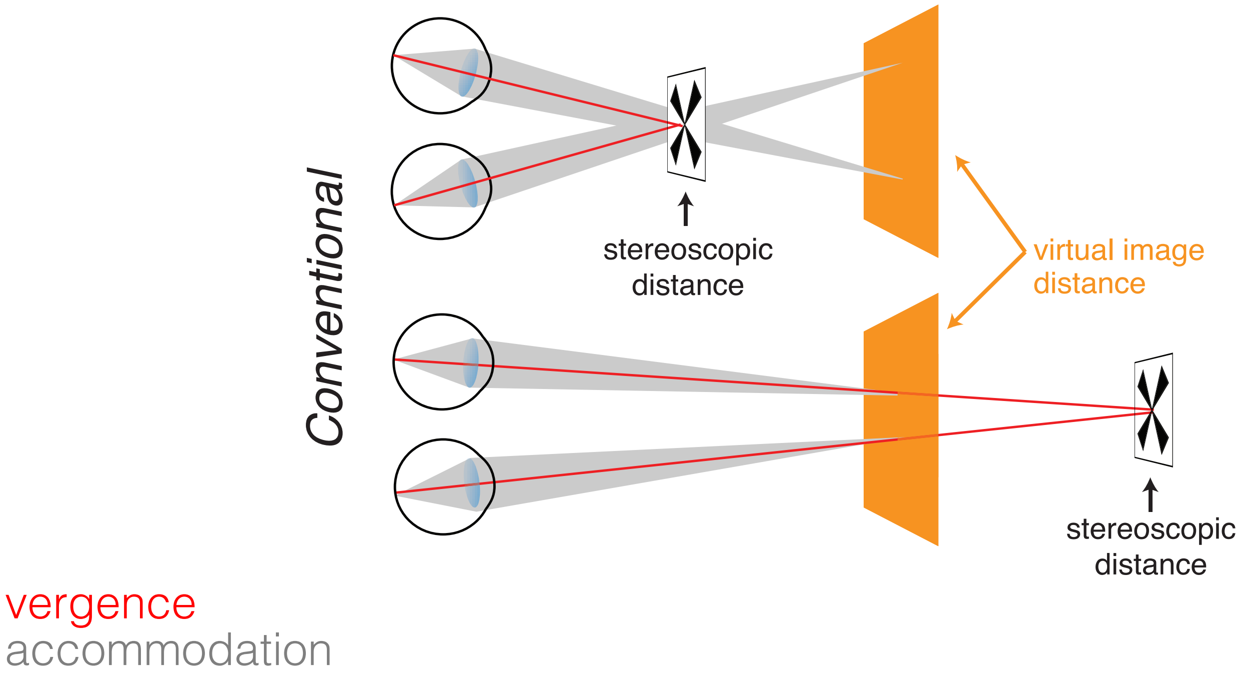
Padmanaban et al., PNAS 2017


Nikon
THORLABS
THORLABS

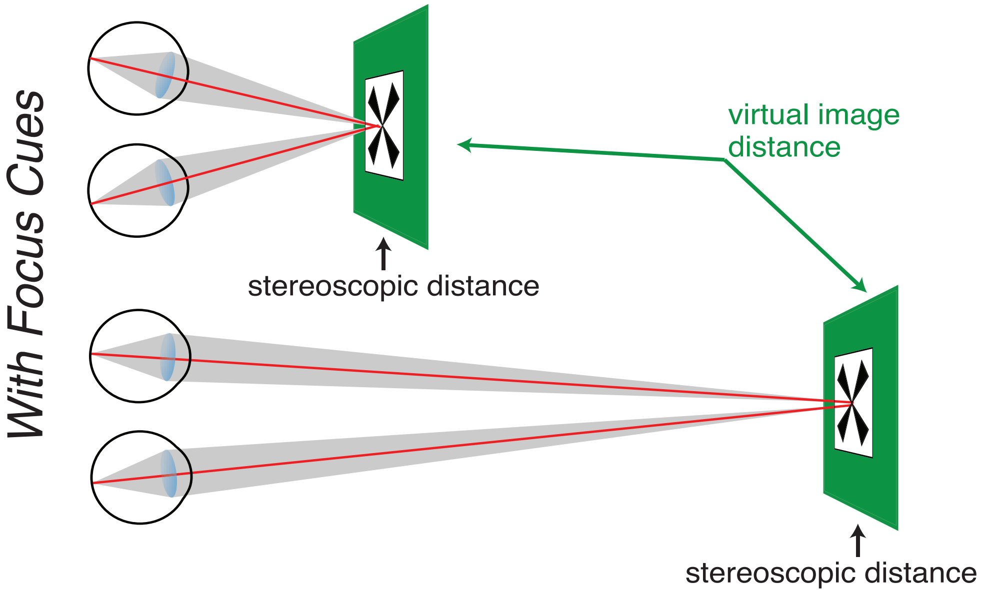

f
f
f
f
f
f
near
far
User Accommodation


f
f
f
f
f
f
near
User Accommodation
far

Conventional Stereo / VR Display

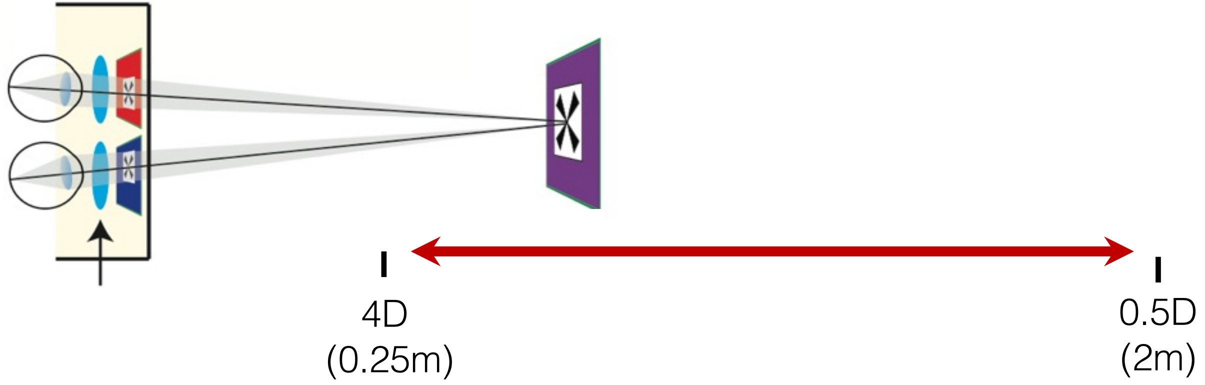


Removing VAC with Varifocal Displays



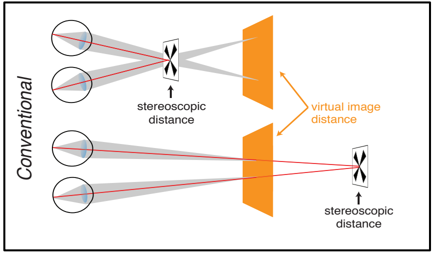
vergence
accommodation

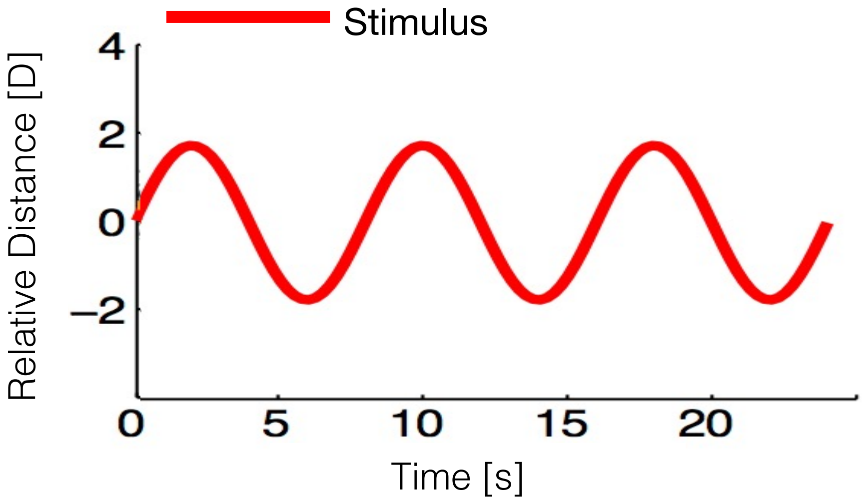
Task



Follow the target with your eyes

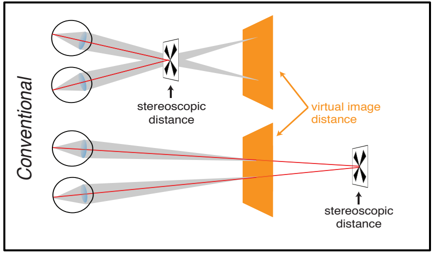
Accommodative Response

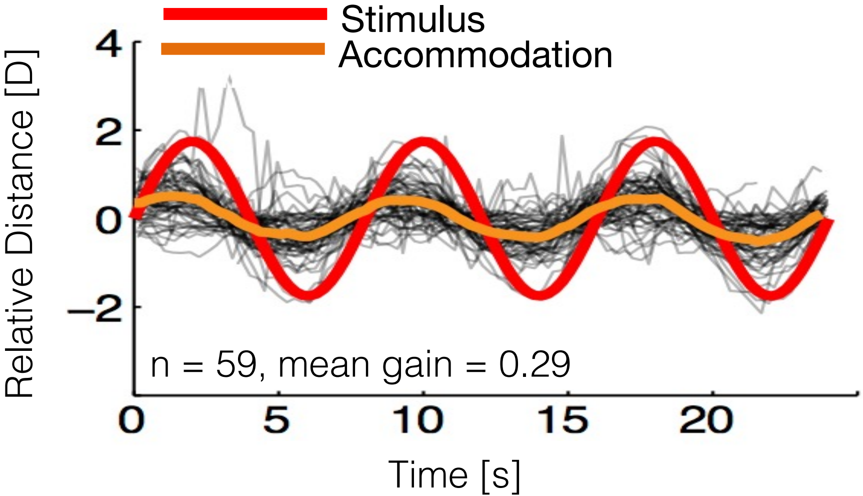




Padmanaban et al., PNAS 2017

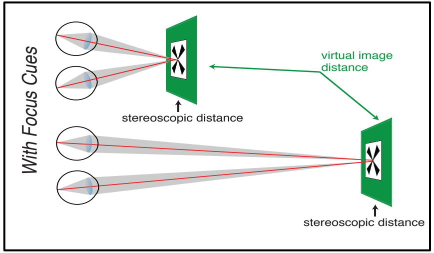
Accommodative Response

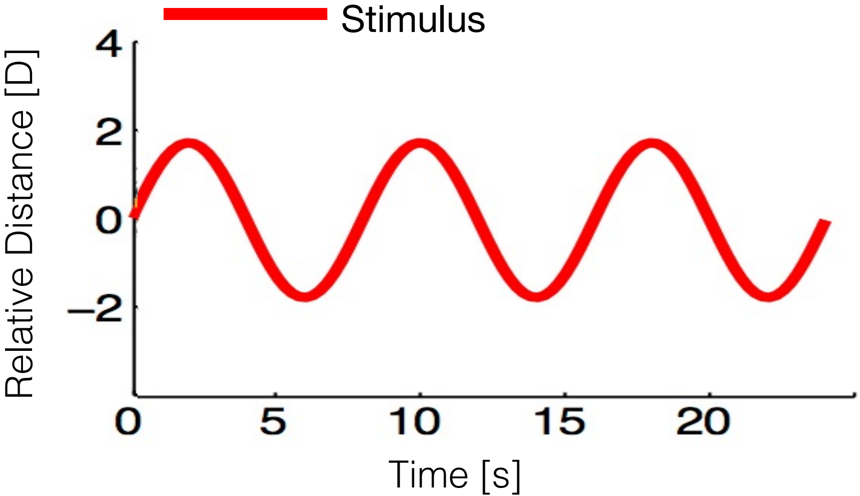




Padmanaban et al., PNAS 2017

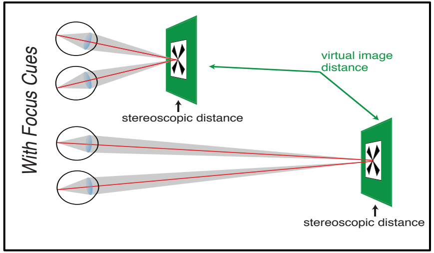
Accommodative Response

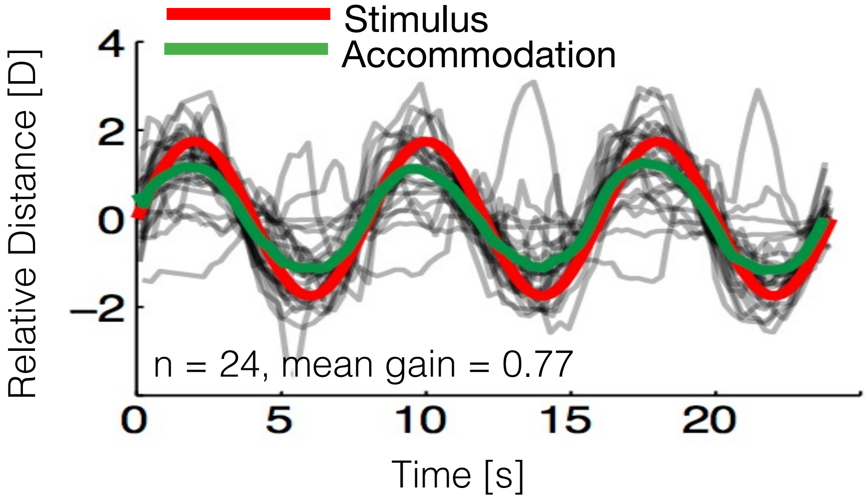




Padmanaban et al., PNAS 2017

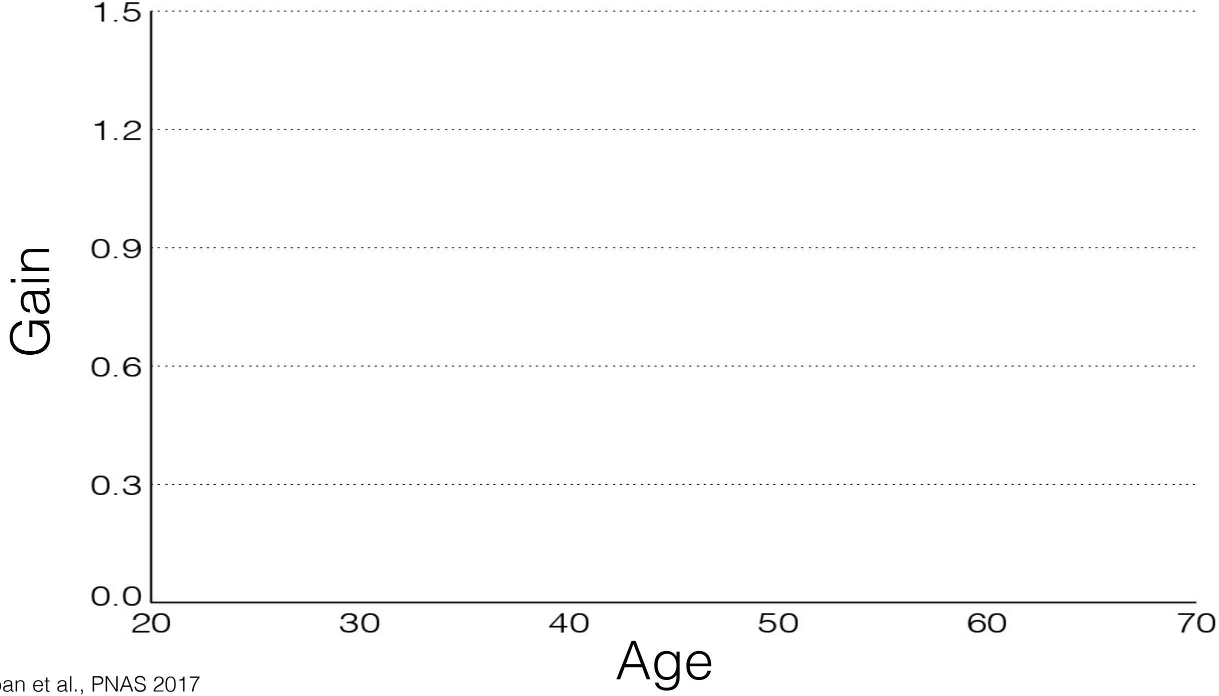
Accommodative Response





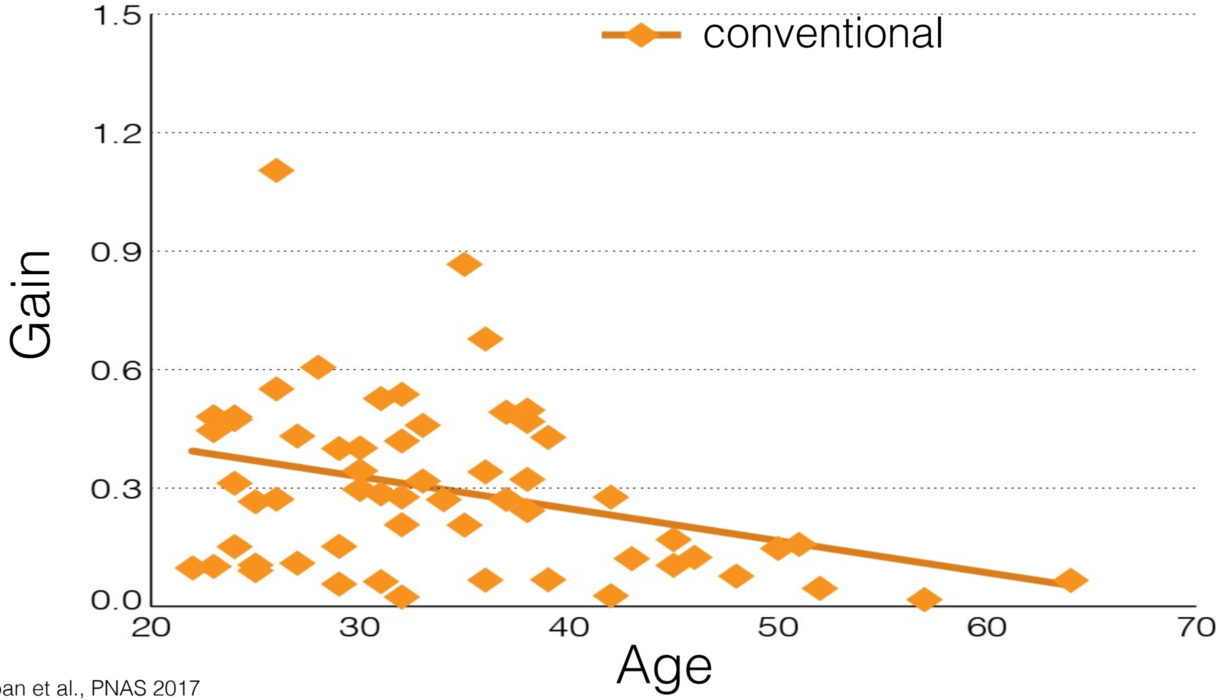
Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?



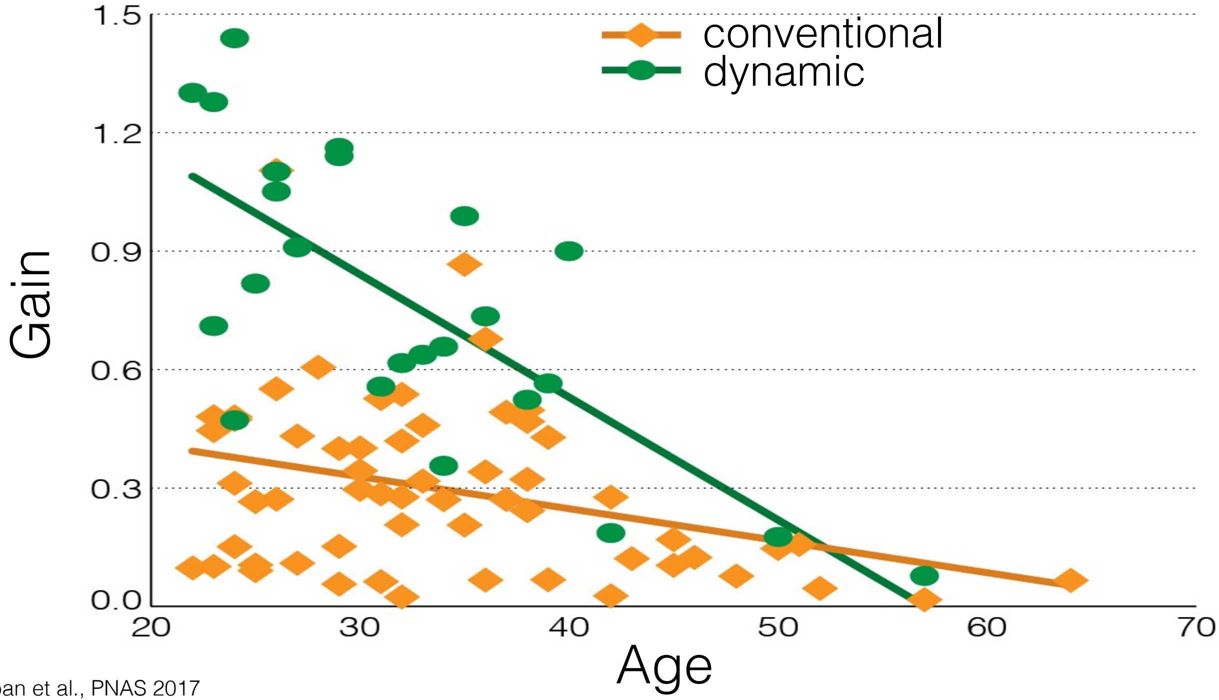
Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?



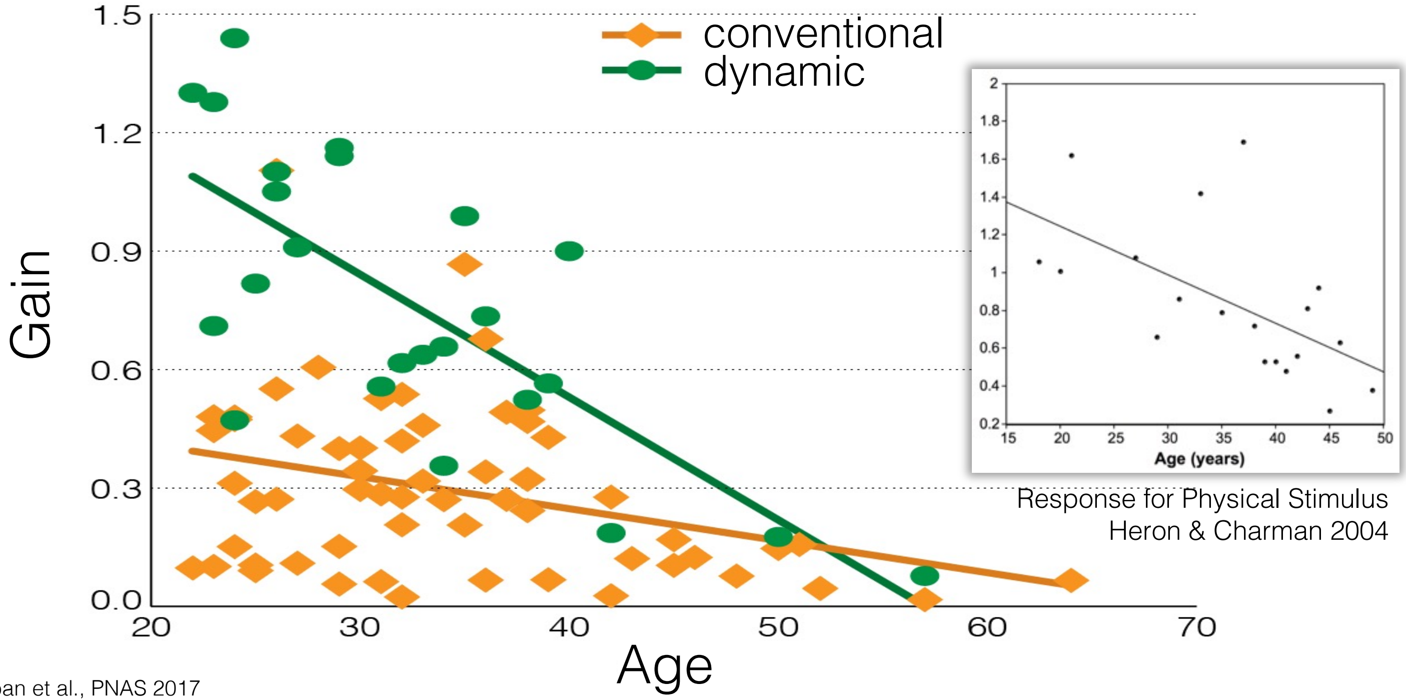
Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?



Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?

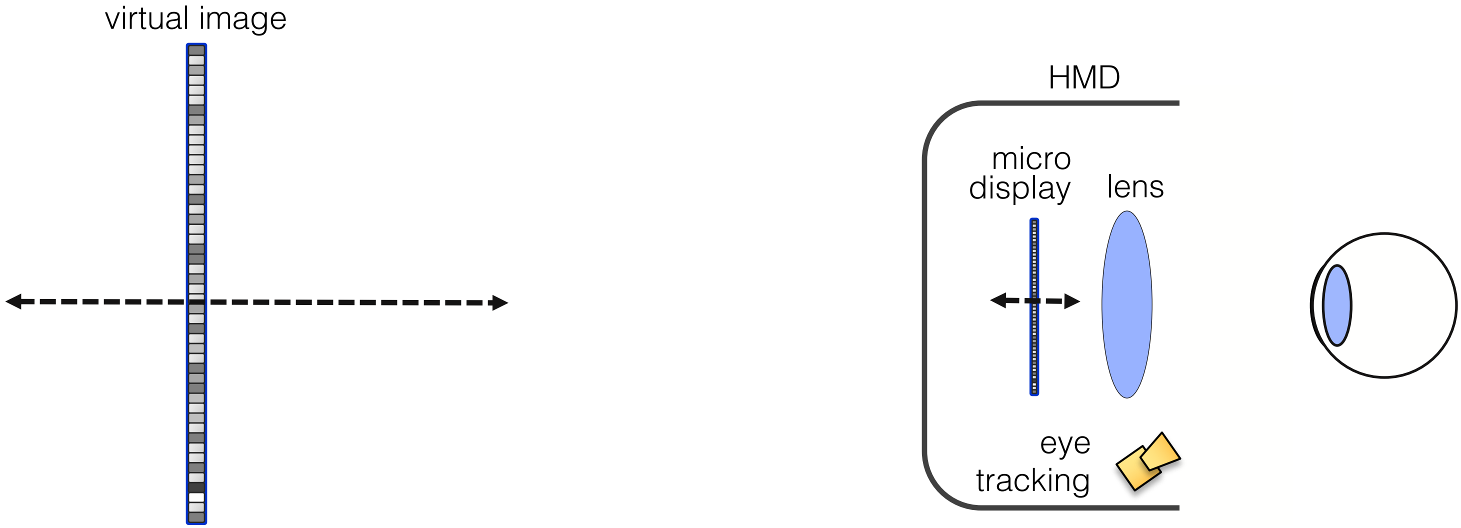


Response for Physical Stimulus
Heron & Charman 2004

Padmanaban et al., PNAS 2017

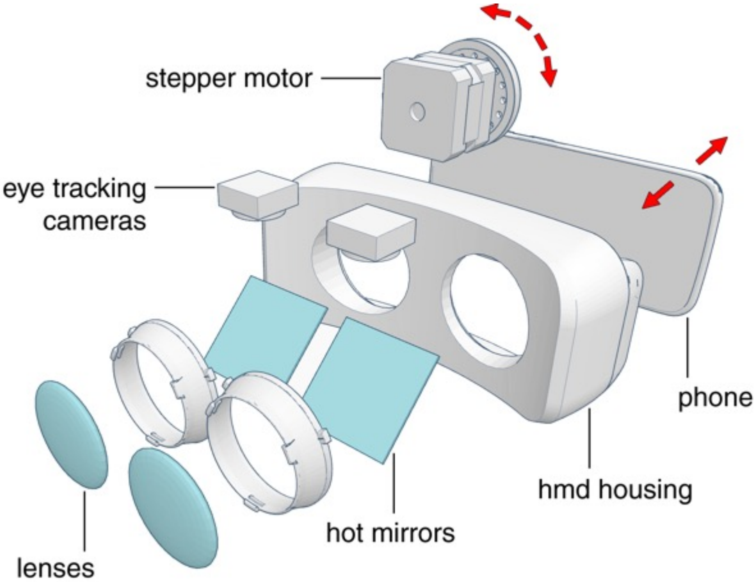
Gaze-contingent Varifocal Displays

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



Padmanaban et al., PNAS 2017

Gaze-contingent Varifocal Displays



Padmanaban et al., PNAS 2017

Gaze-contingent Varifocal Displays

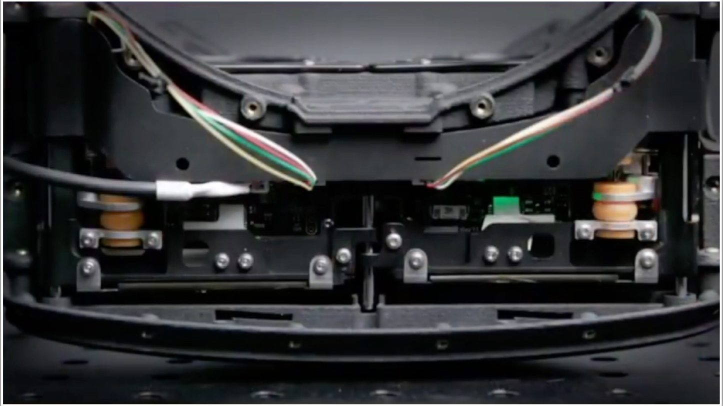
Padmanaban et al., PNAS 2017

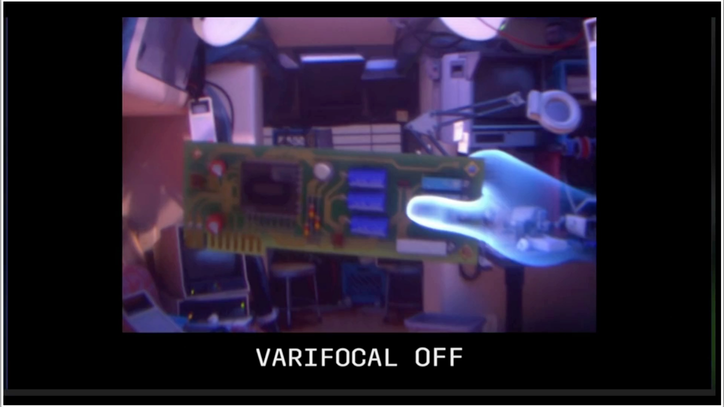
Gaze-contingent Varifocal Displays

Padmanaban et al., PNAS 2017

at ACM SIGGRAPH 2016

Oculus Half Dome Prototype

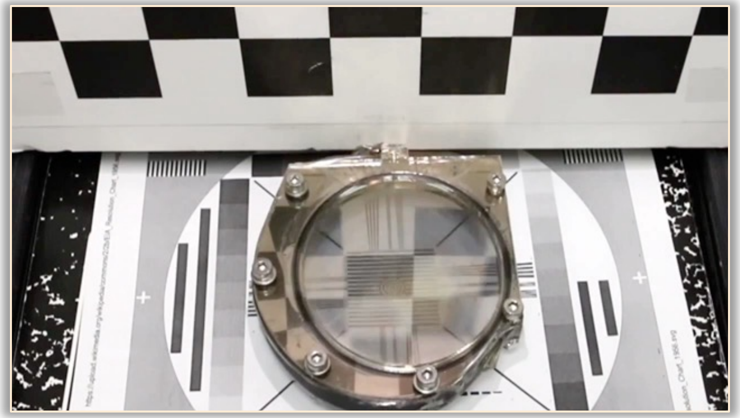




Oculus announces gaze-contingent varifocal display at F8, 05/2018

Video courtesy of Facebook/Oculus

Varifocal AR Displays



Dunn et al. “Wide Field of View Varifocal Near-Eye Display using See-through Deformable Membrane Mirrors”, IEEE TVCG 2017

Summary

- adaptive focus drives accommodation and can also correct for refractive errors (myopia, hyperopia)

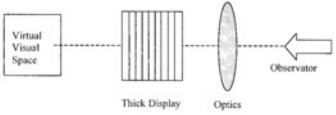
- gaze-contingent focus gives natural focus cues for non-presbyopes, but require eyes tracking

- presbyopes require fixed focal plane with correction

VR Displays with Focus Cues

2. Multiplane Displays

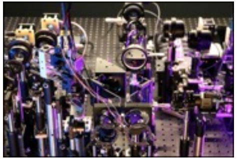
Multiplane VR Displays



idea introduced
Rolland et al. 2000

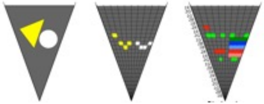
benchtop prototype
Akeley 2004

near-eye display prototype
Liu 2008, Love 2009



Mercier et al. 2017

Chang et al. 2018



Rathinavel et al. 2018

- 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 ...

Challenges of Multiplane VR Displays

- when implemented with focus-tunable optics & time-multiplexing in VR: *flicker*
- when implemented with multiple optically overlaid microdisplays in VR or multiple waveguides in AR: *system complexity and calibration*
- multifocal plane displays require image focal plane decomposition – computationally expensive
- decompositions are sensitive to eye position – also need eye tracking, so why not just do varifocal?

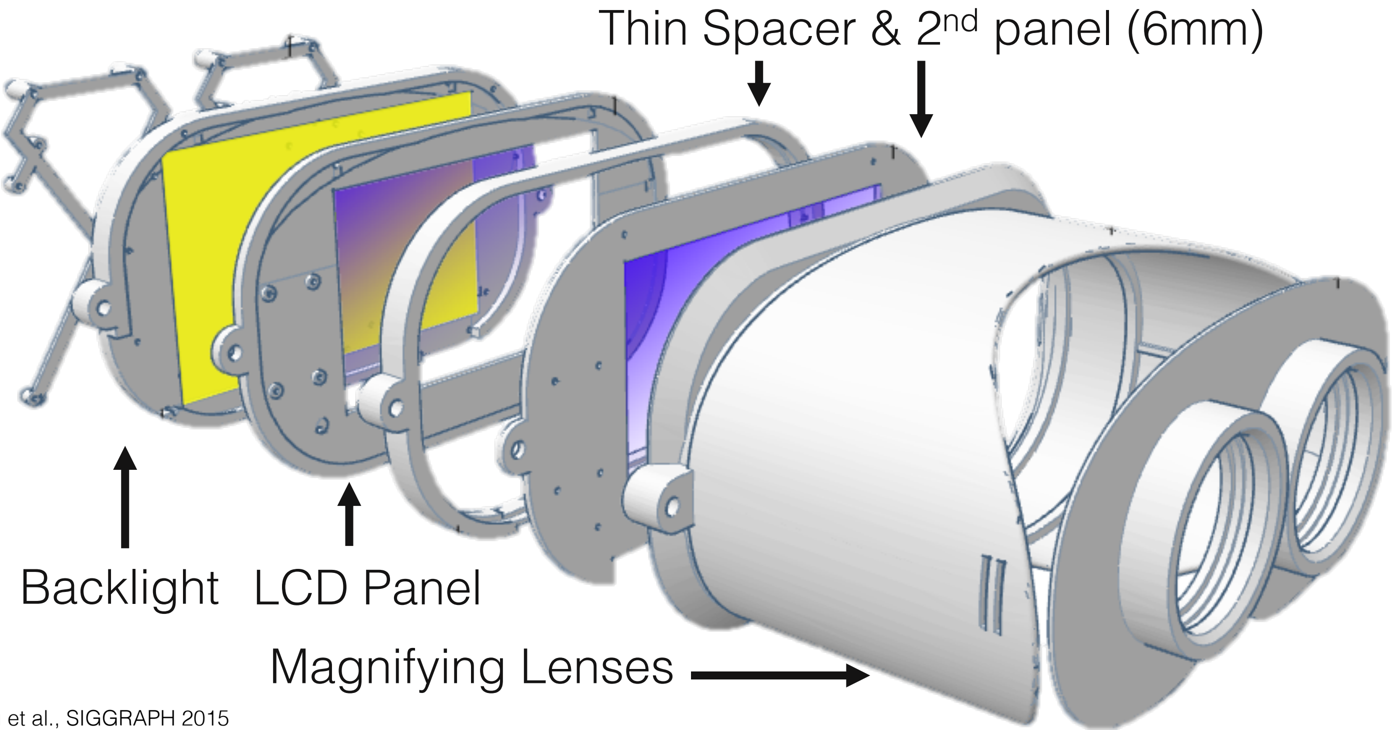
VR Displays with Focus Cues

3. Light Field Displays

Light Field Stereoscope

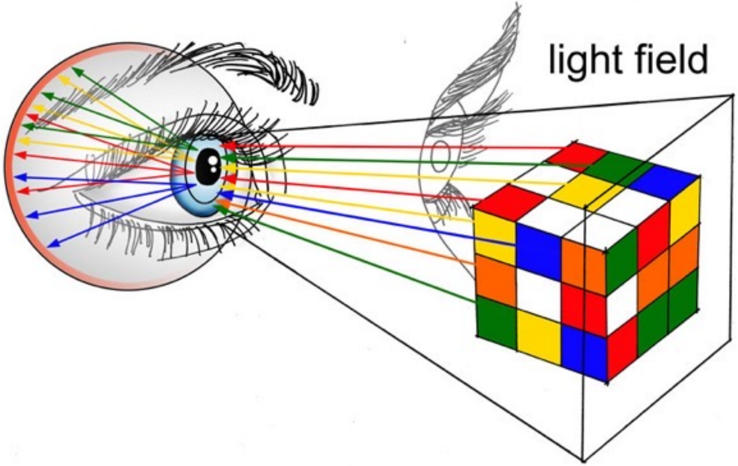
Huang et al., SIGGRAPH 2015

Light Field Stereoscope



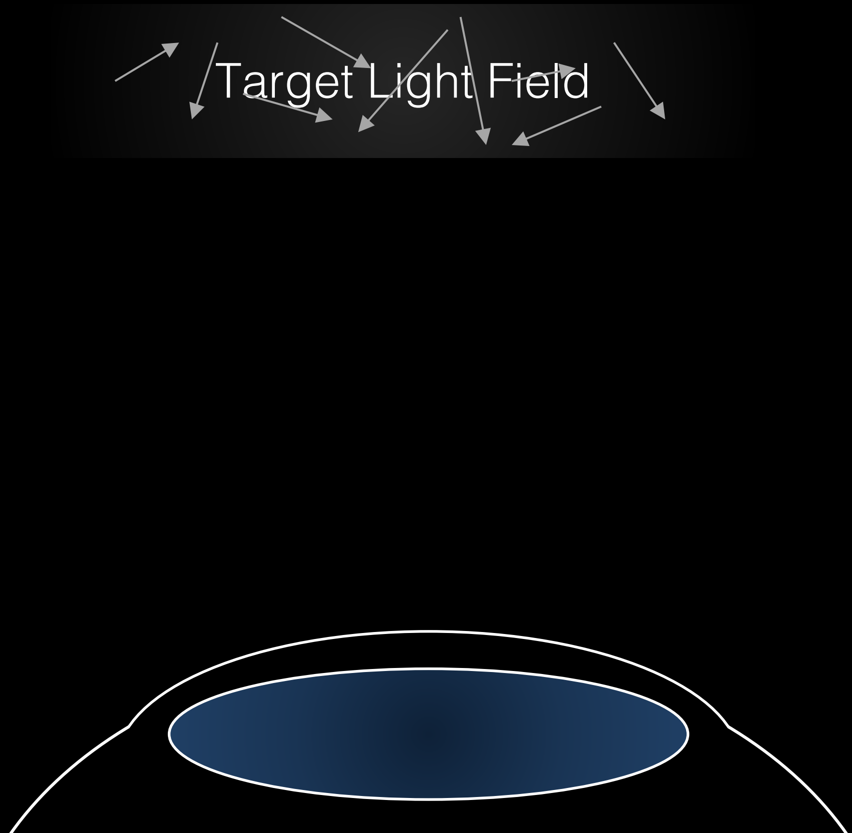
Huang et al., SIGGRAPH 2015

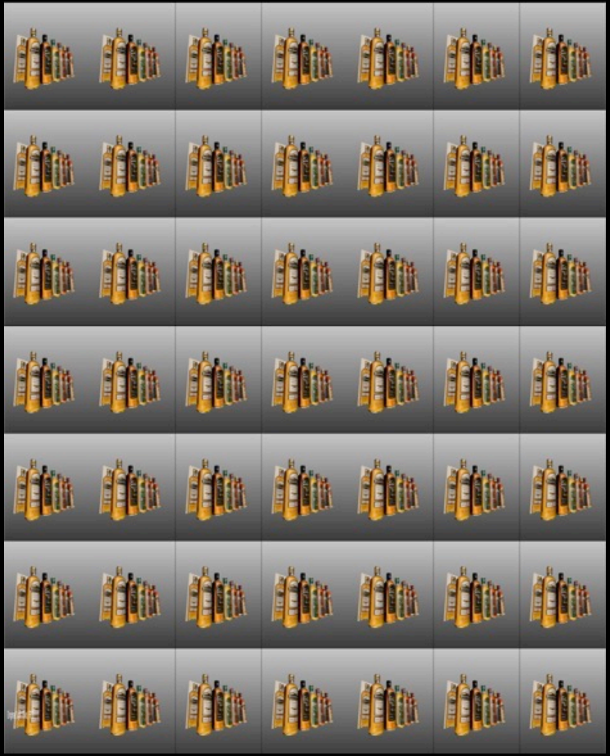
Near-eye Light Field Displays



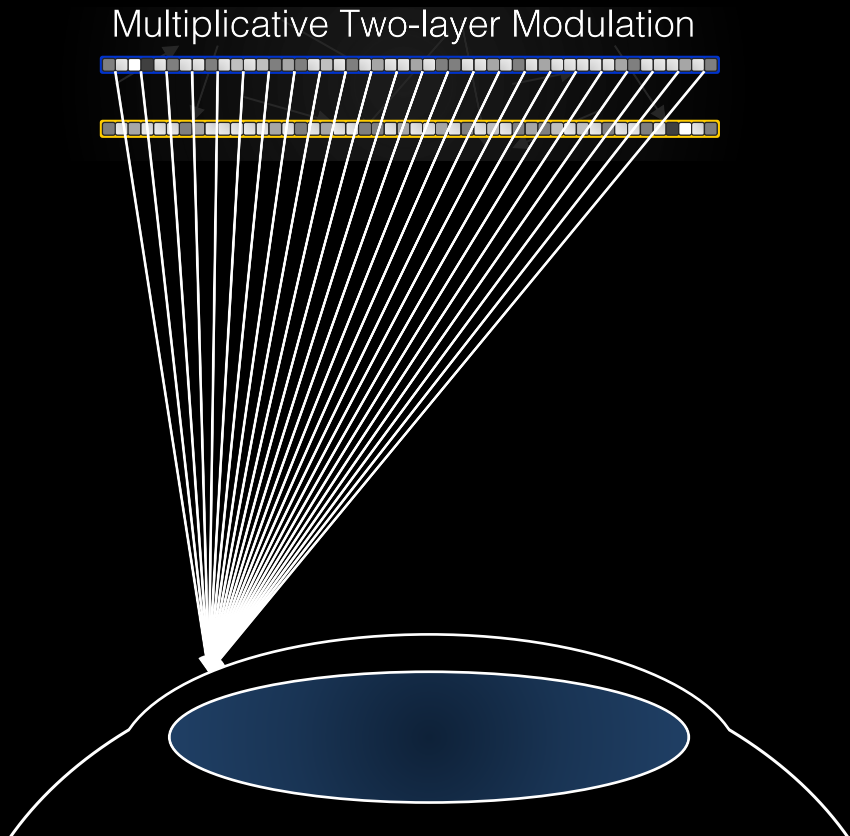
Idea: project multiple different perspectives into different parts of the pupil!

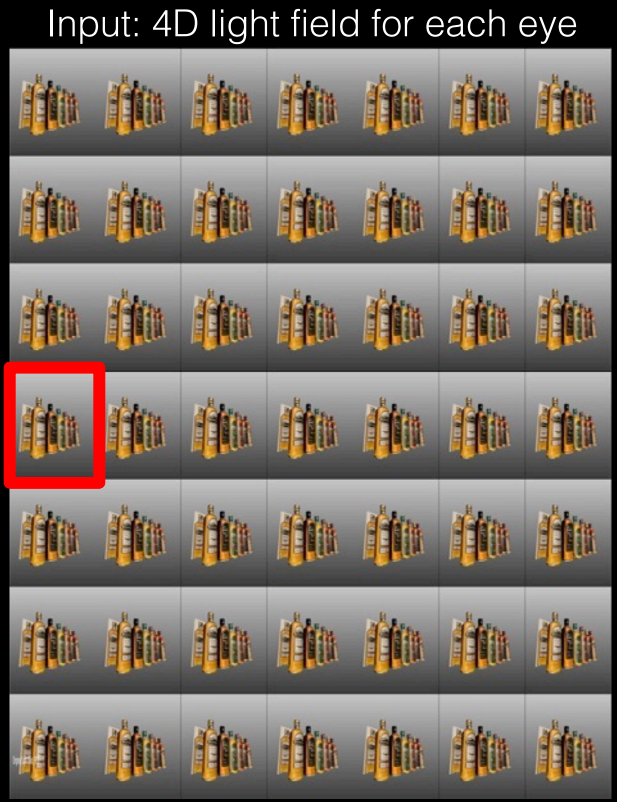
Input: 4D light field for each eye





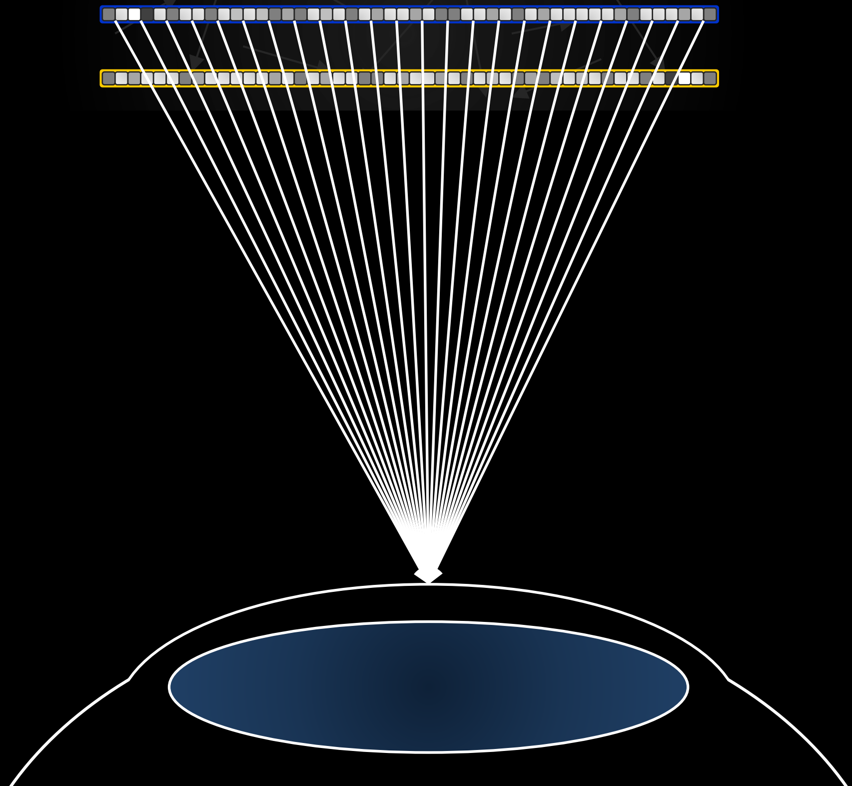
Model Courtesy of Bushmills Irish Whiskey



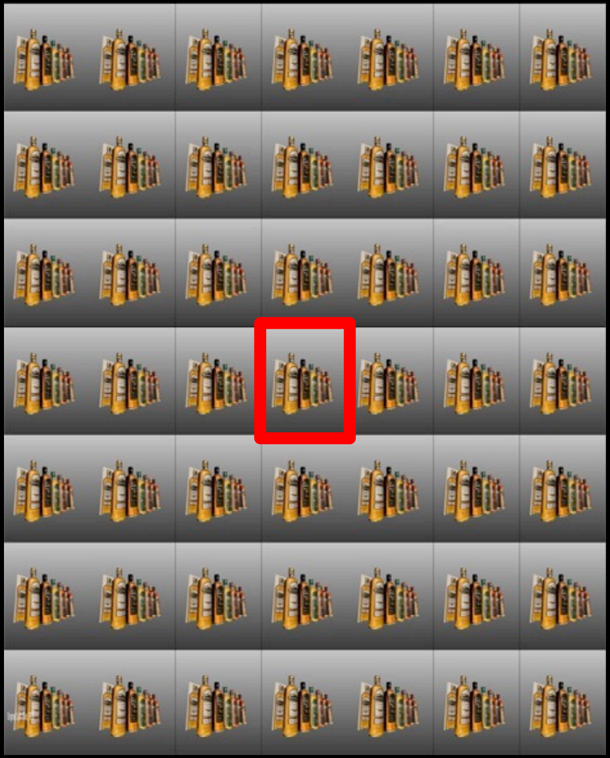


Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation

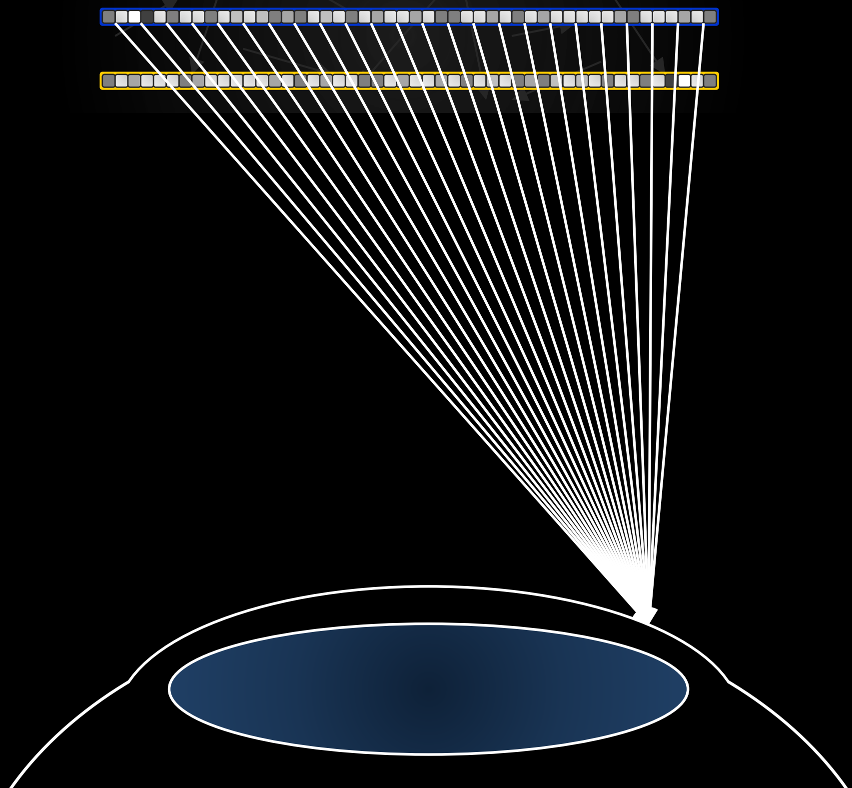


Input: 4D light field for each eye

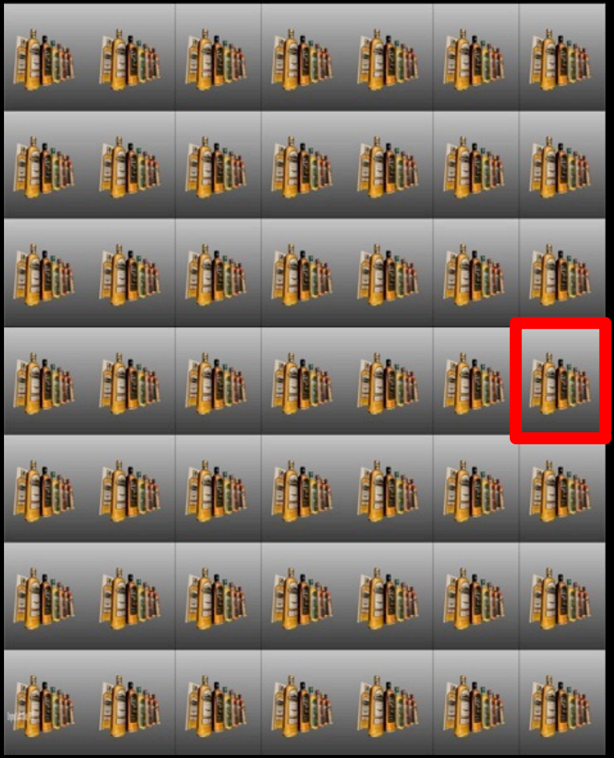


Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation

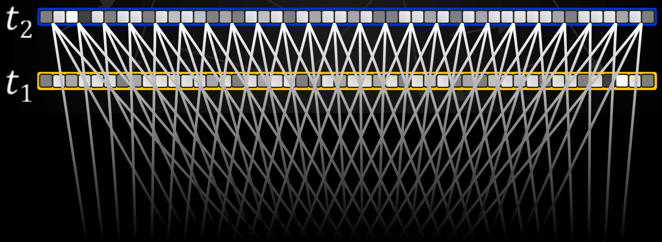


Input: 4D light field for each eye



Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation



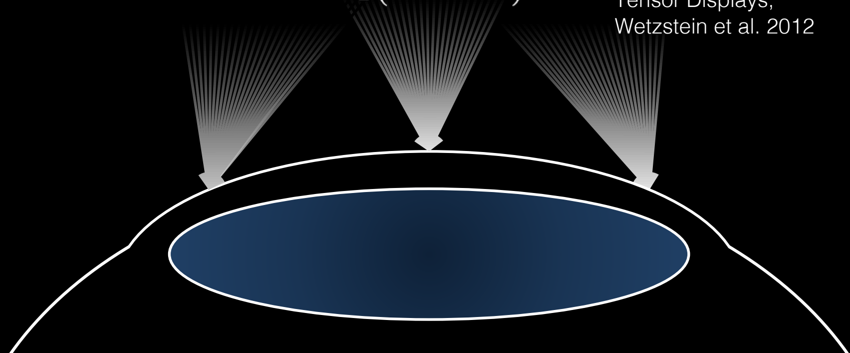
$$\underset{\{t_1, t_2\}}{minimize} \; \|\beta \mathrm{l} - (\phi_1 t_1) \circ (\phi_2 t_2)\|^2 \quad s.t. \; 0 \leq \; t_1, t_2 \leq 1$$

Reconstruction:

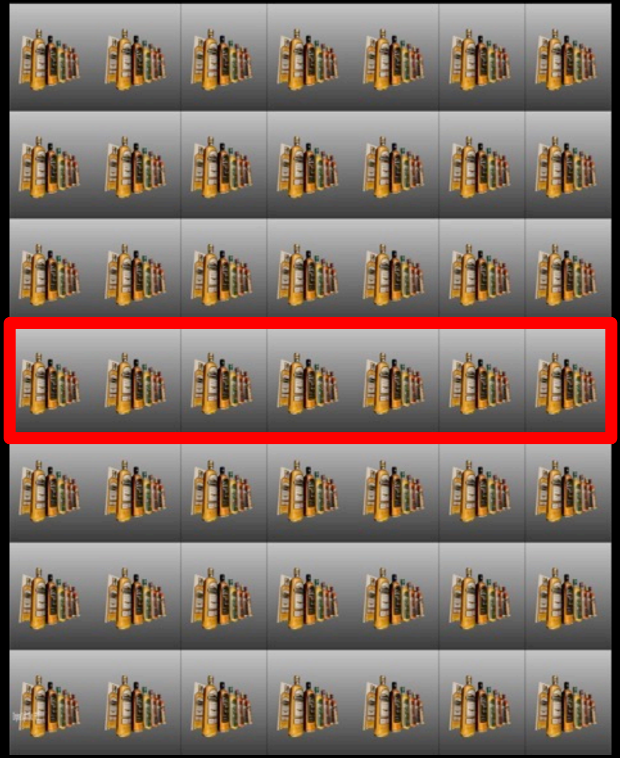
$$t_1 \leftarrow t_1 \circ \frac{\phi_1^T(\beta \mathrm{l} \circ (\phi_2 t_2))}{\phi_1^T\left(\tilde{\mathrm{l}} \circ (\phi_2 t_2)\right) + \epsilon}$$

for layer t_1

Tensor Displays,
Wetzstein et al. 2012

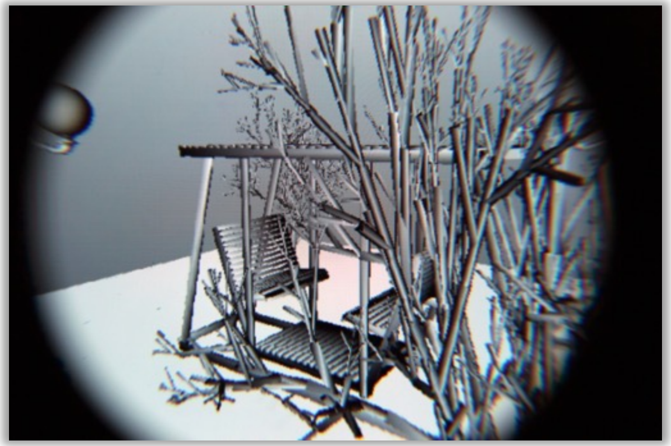


Input: 4D light field for each eye



Model Courtesy of Bushmills Irish Whiskey

Light Field Stereoscope

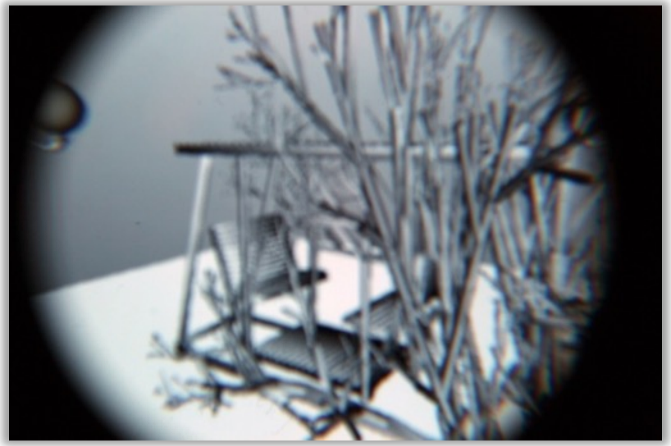


Traditional HMDs
- No Focus Cues

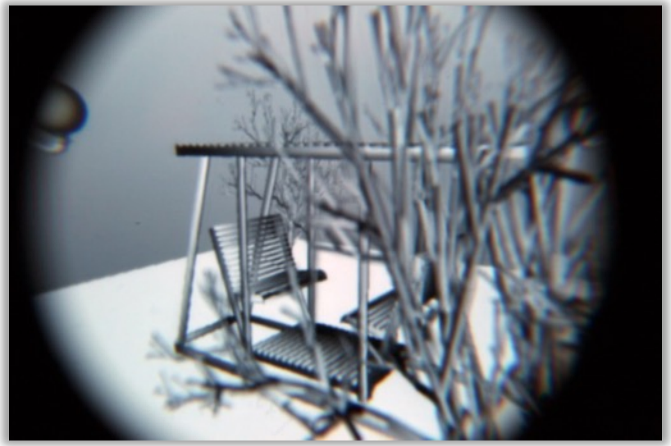
The Light Field HMD
Stereoscope

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



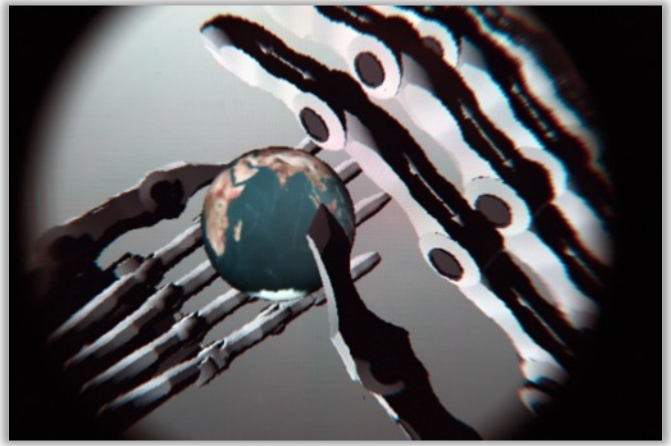
Traditional HMDs
- No Focus Cues



The Light Field HMD
Stereoscope

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



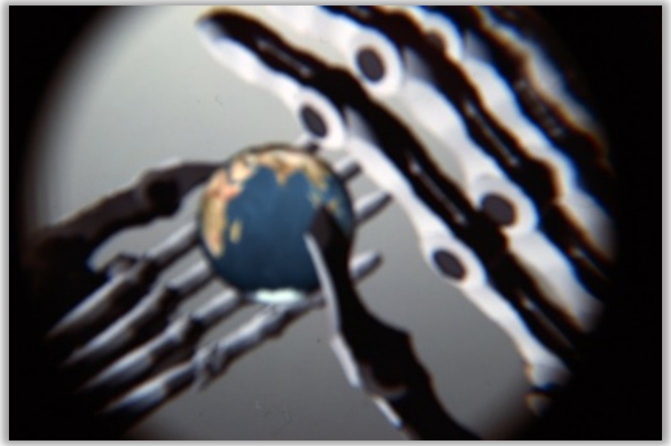
Traditional HMDs
- No Focus Cues

The Light Field HMD
Stereoscope

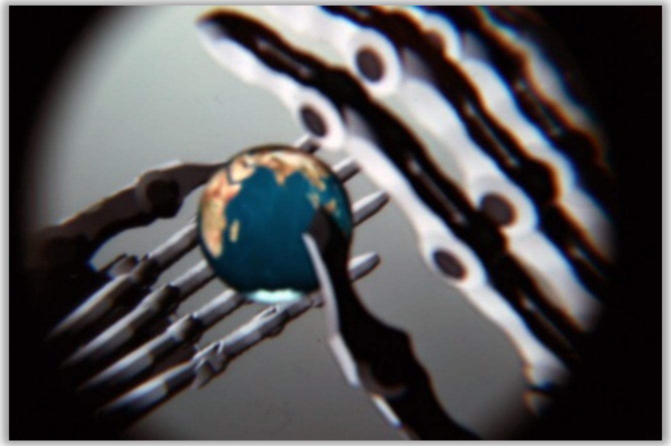
Model Courtesy of Paul H. Manning

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



Traditional HMDs
- No Focus Cues

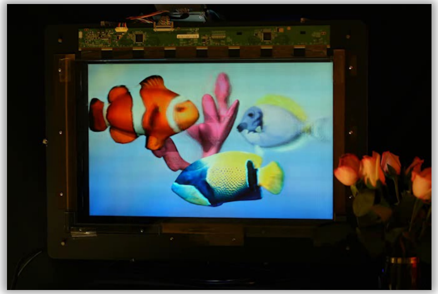


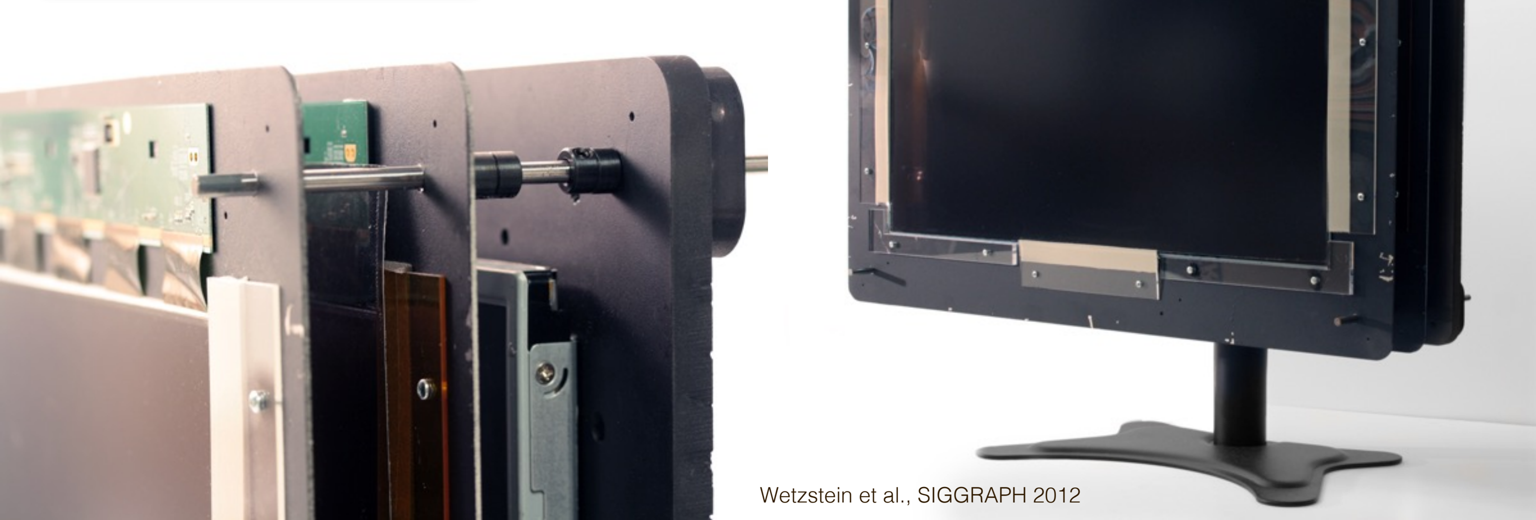
The Light Field HMD
Stereoscope

Model Courtesy of Paul H. Manning

Huang et al., SIGGRAPH 2015

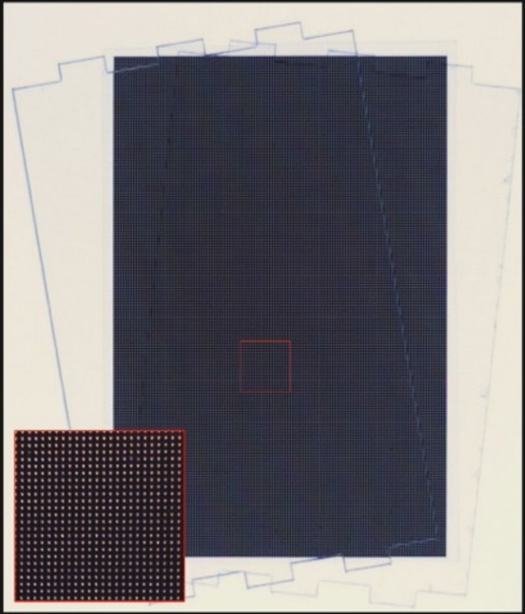
Tensor Displays

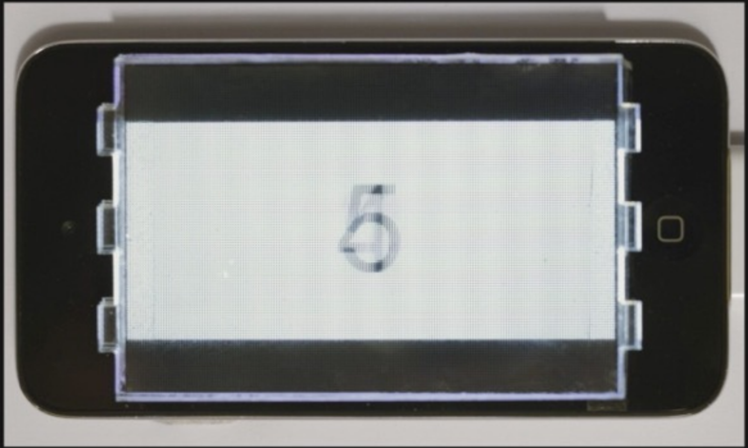




Wetzstein et al., SIGGRAPH 2012

Vision-correcting Display





printed transparency

iPod Touch prototype

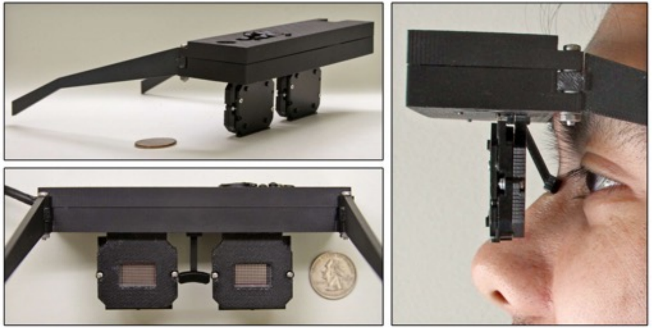
Huang et al., SIGGRAPH 2014

300 dpi or higher

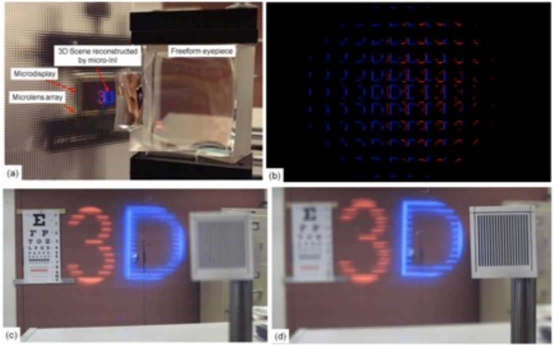
prototype

Huang et al., SIGGRAPH 2014

Microlens-based Near-eye Light Field Displays



Thin VR version:
Lanman and Luebke, 2013



Optical see-through AR version:
Hua and Javidi, 2014

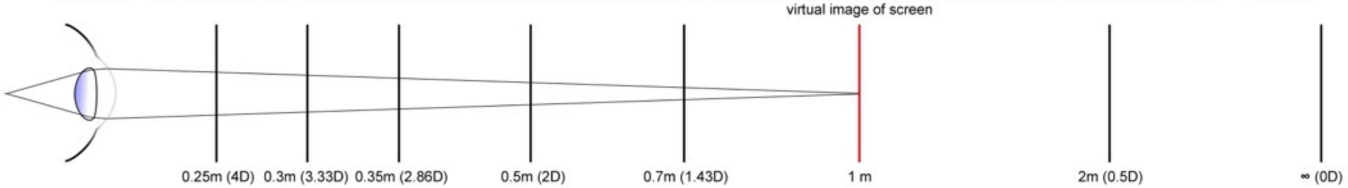
- biggest downside: usually low resolution
- limited by spatio-angular resolution tradeoff and, more fundamentally, also diffraction

VR Displays with Focus Cues

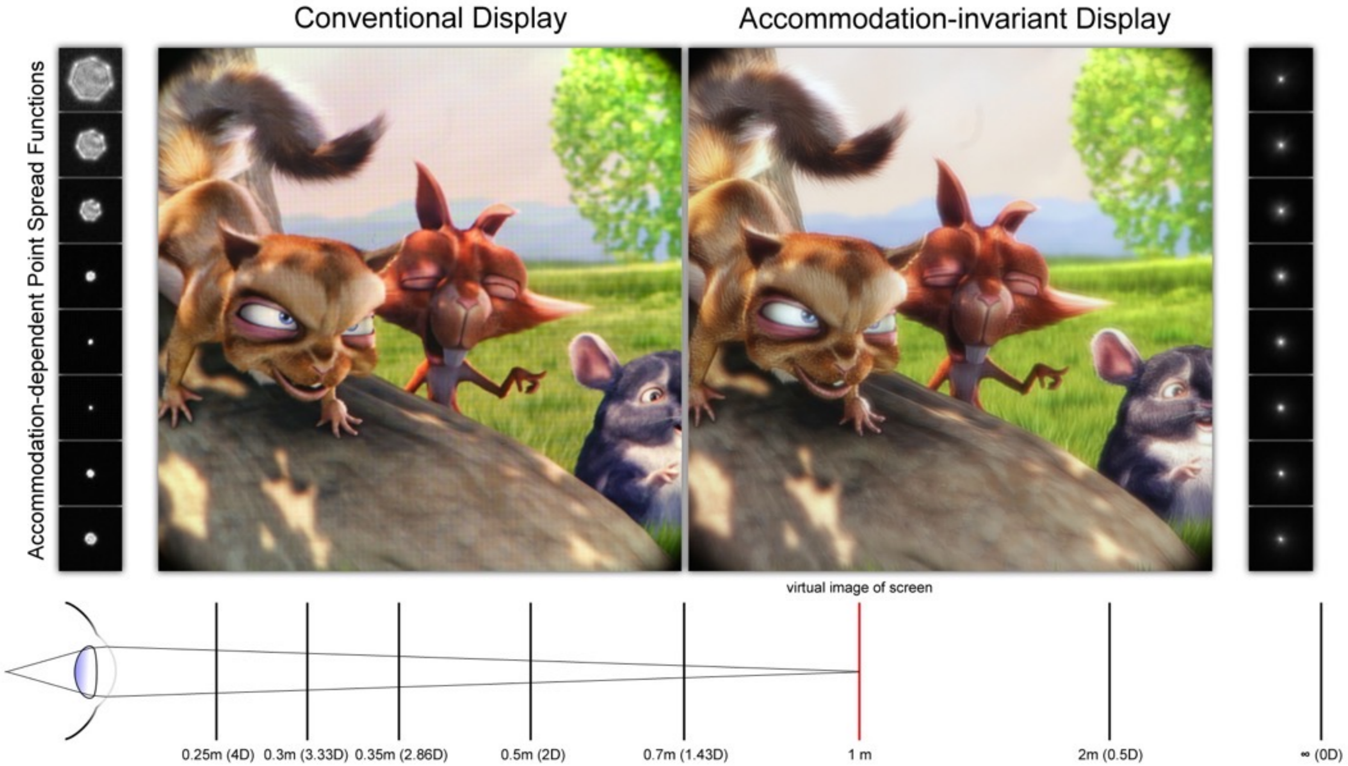
4. Maxwellian-type Displays

Blur Gradient Driven Accommodation

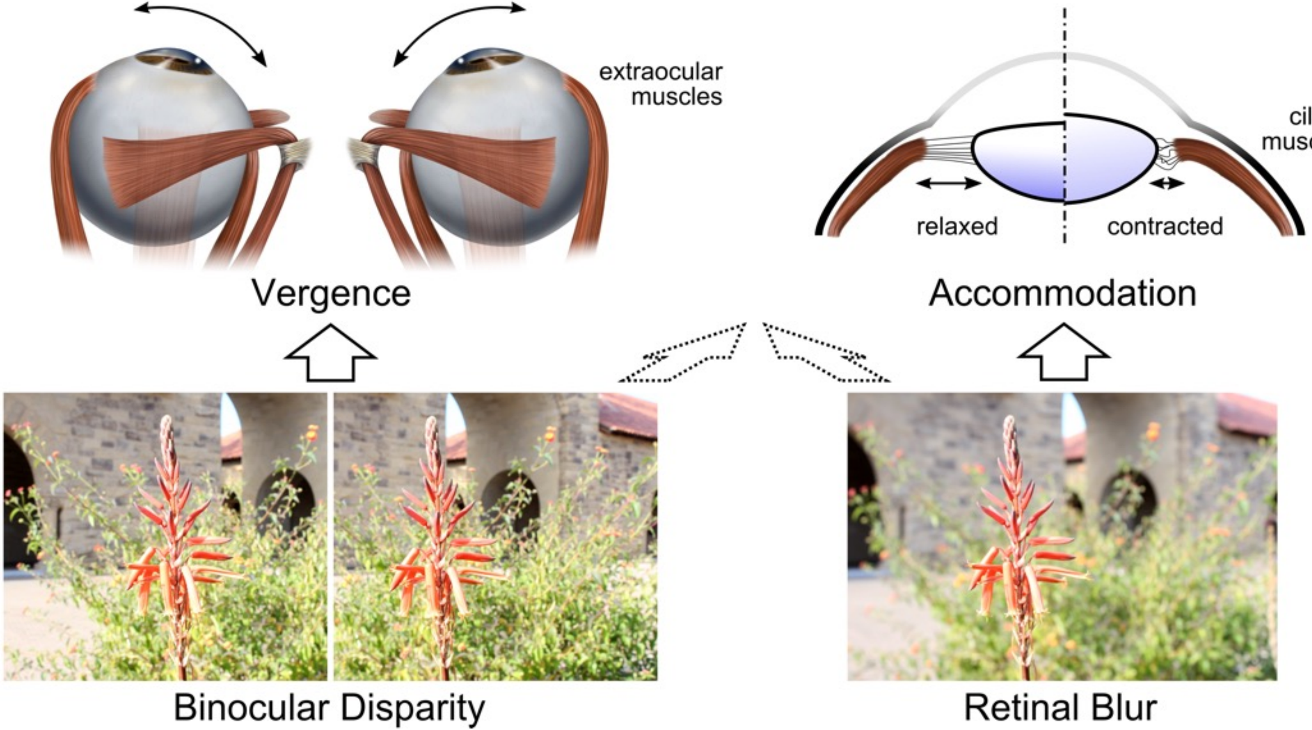
Conventional Display

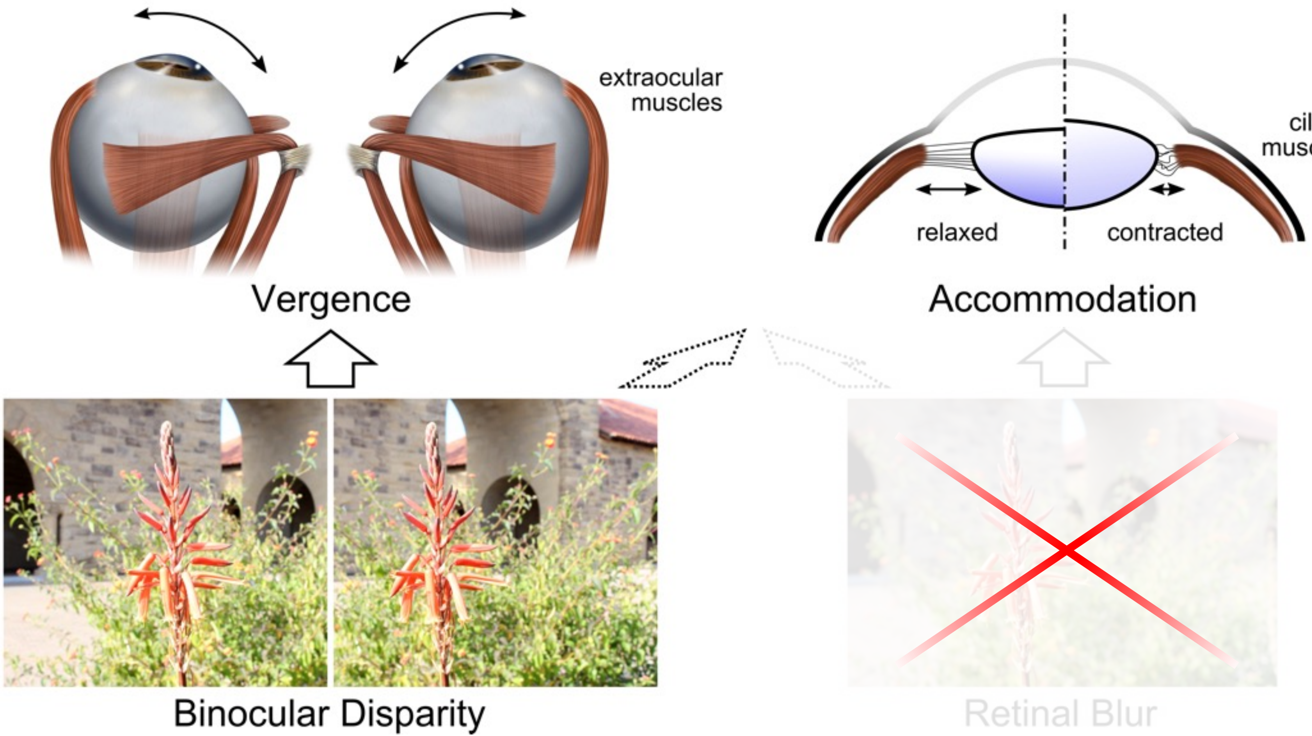


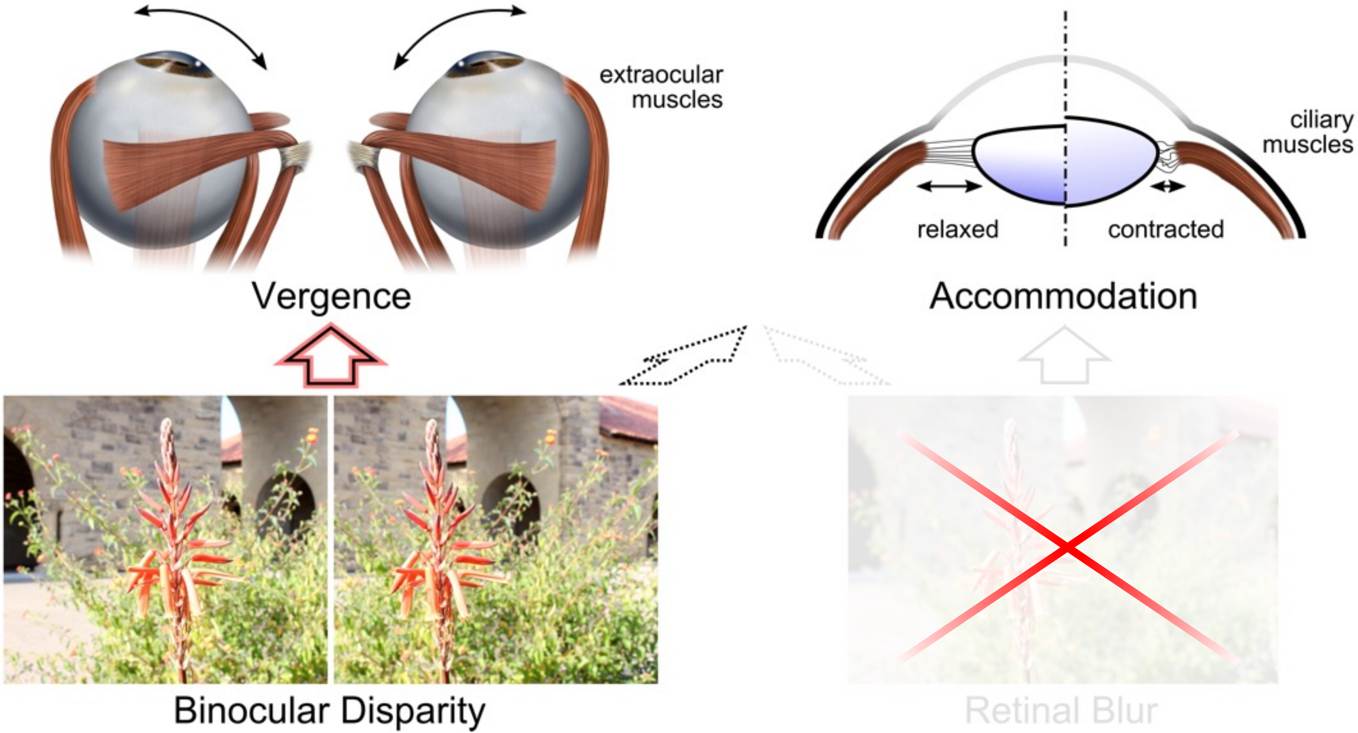
PSF Engineering

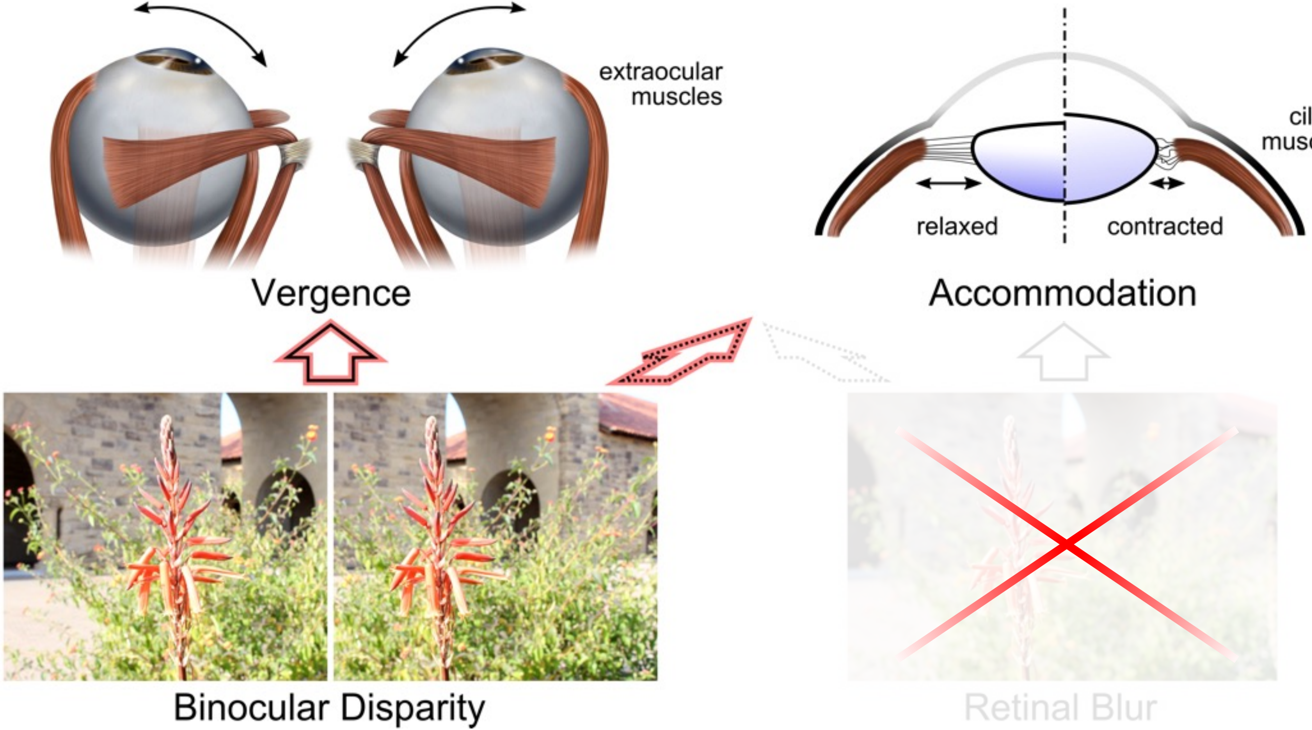


Q: can we drive accommodation with stereoscopic cues by optically removing the retinal blur cue?


extraocular
muscles
Vergence
ciliary
muscles
relaxed
contracted
Accommodation
Binocular Disparity
Retinal Blur


extraocular muscles
ciliary muscles
relaxed
contracted
Vergence
Accommodation
Binocular Disparity
Retinal Blur


extraocular
muscles
ciliary
muscles
relaxed
contracted
Vergence
Accommodation
Binocular Disparity
Retinal Blur


extraocular
muscles
ciliary
muscles
relaxed
contracted
Vergence
Accommodation
Binocular Disparity
Retinal Blur

How do we remove the blur cue?

Aperture Controls Depth of Field

Image courtesy of Concept One Studios

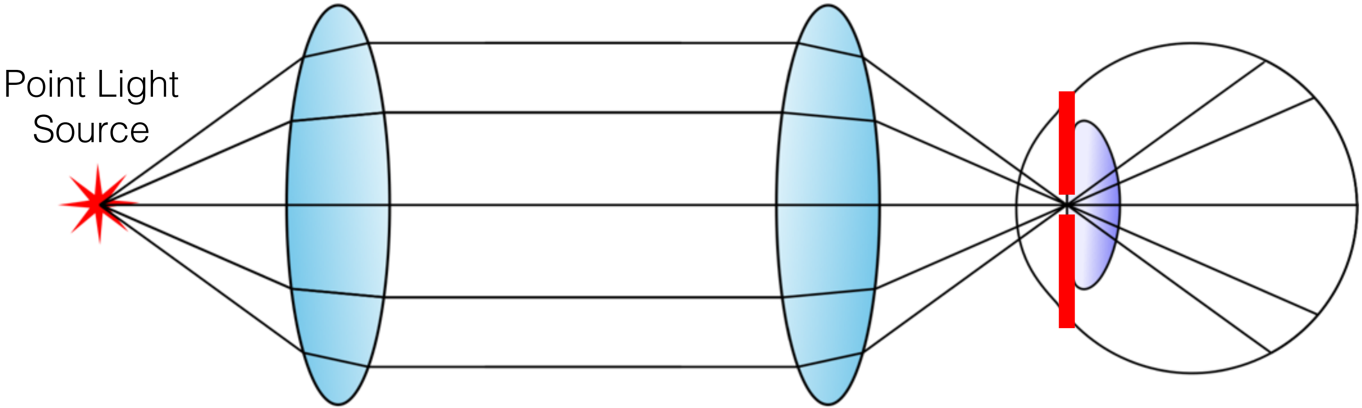
Aperture Controls Depth of Field

Image courtesy of Concept One Studios

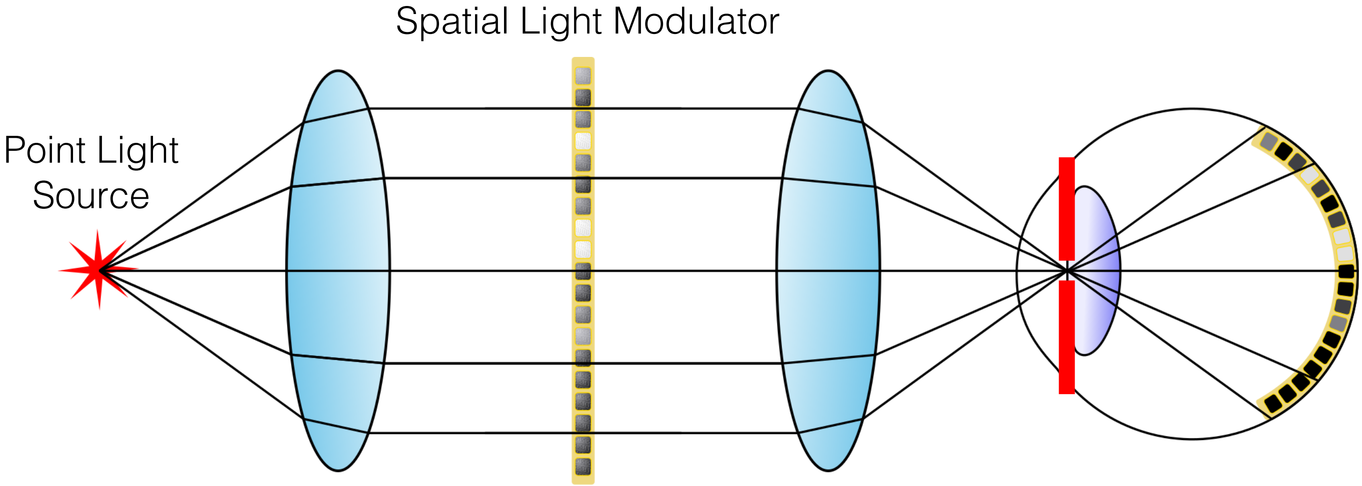
Aperture Controls Depth of Field

Image courtesy of Concept One Studios

Maxwellian-type (pinhole) Near-eye Displays

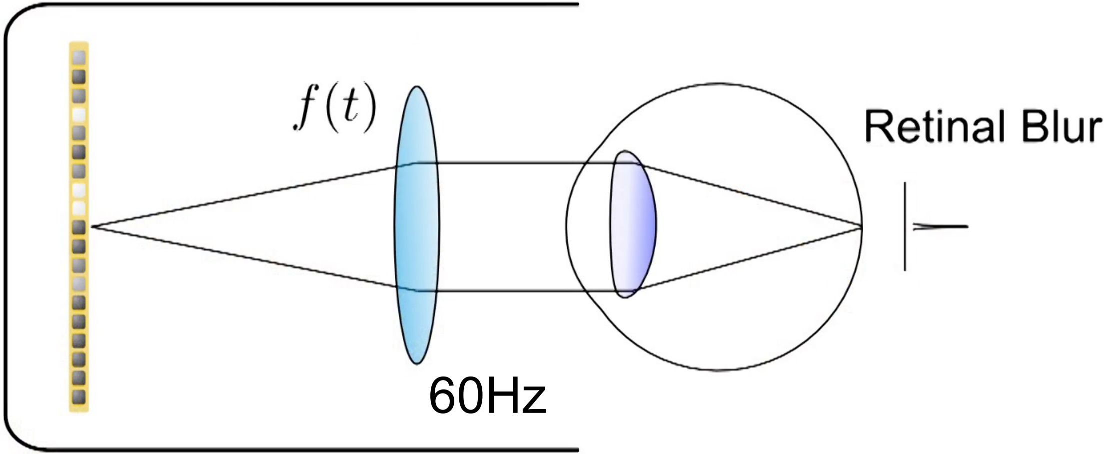


Maxwellian-type (pinhole) Near-eye Displays



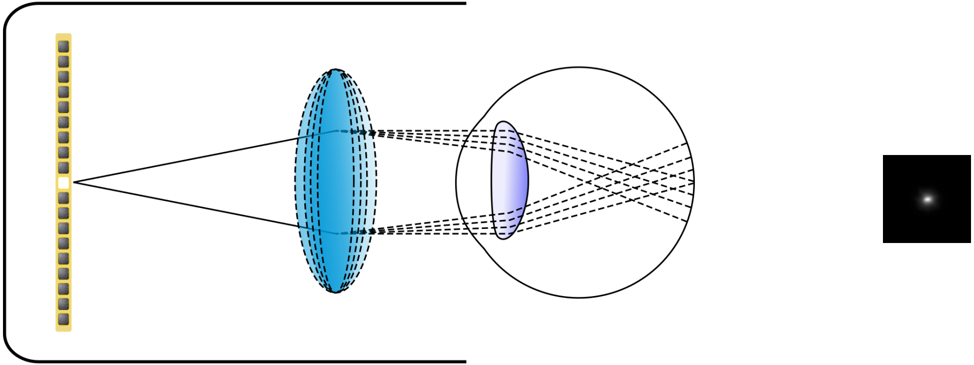
Severely reduces eyebox; requires dynamic steering of exit pupil

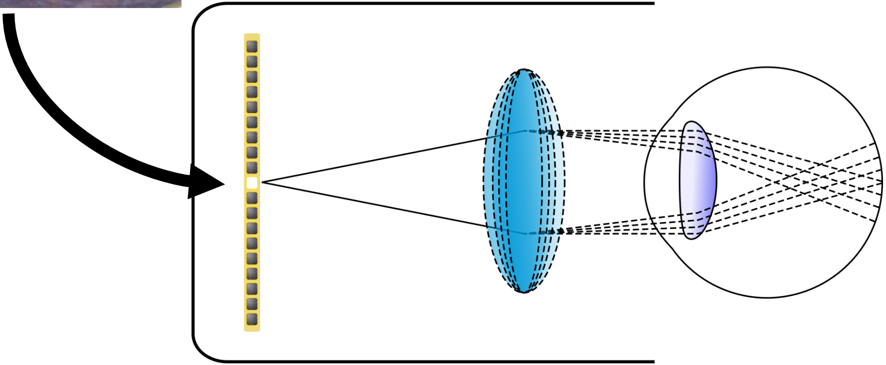
Focal Sweep

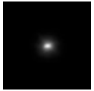


EDOF Cameras:

Dowski & Cathey, App. Opt. 1995
Nagahara et al., ECCV 2008
Cossairt et al., SIGGRAPH 2010

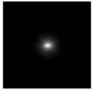


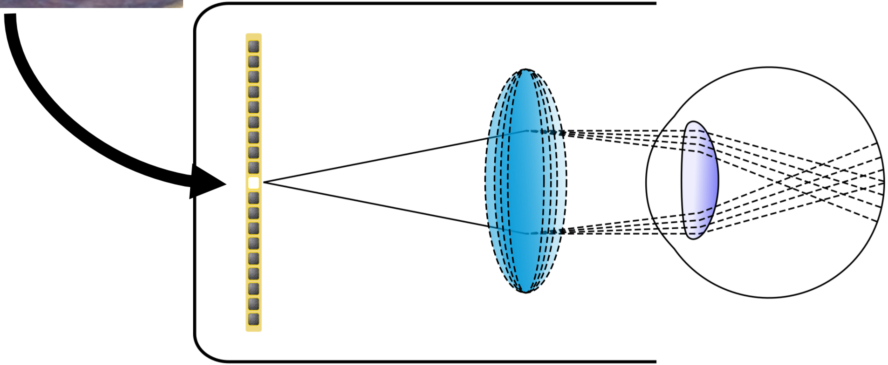


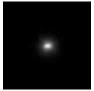


Convolution

*

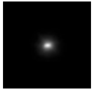






Convolution

*



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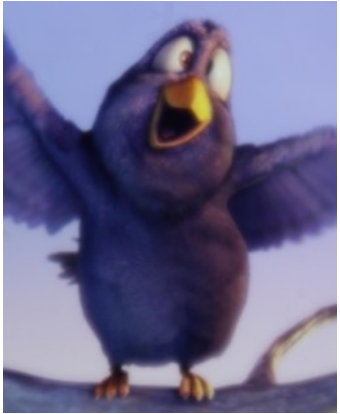
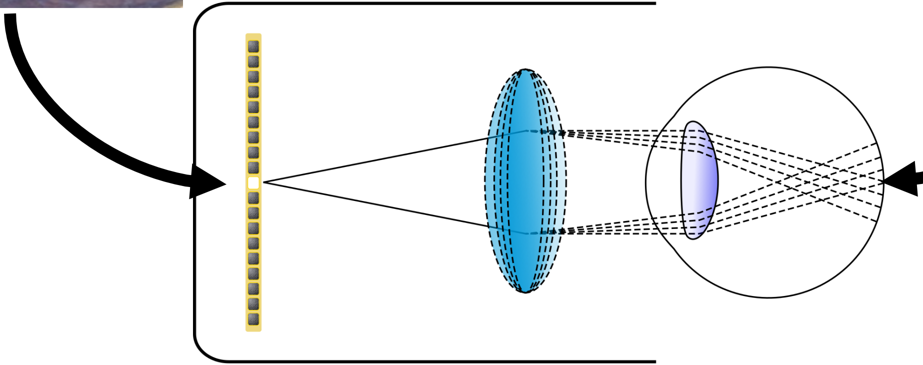
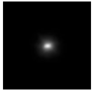
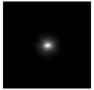
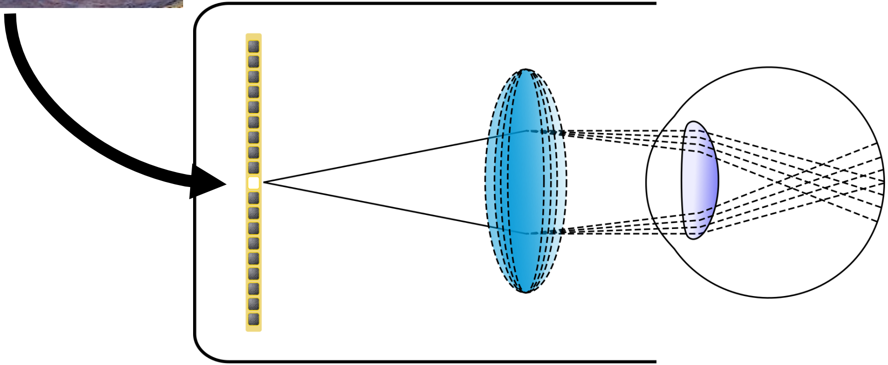


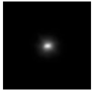




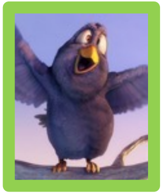
Deconvolution





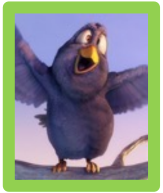


Target

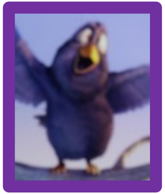


Target Image

Target



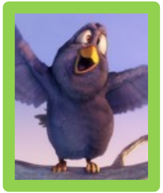
Conventional



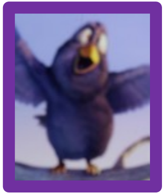
Target Image

Conventional Display @ 1D

Target

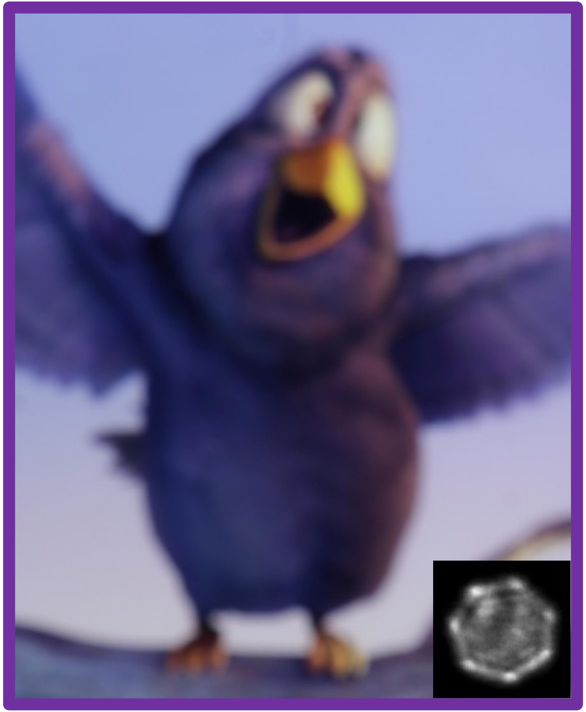


Conventional

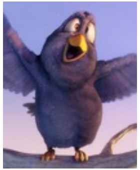


Target Image

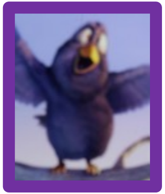
Conventional Display @ 3D



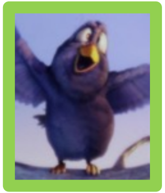
Target



Conventional

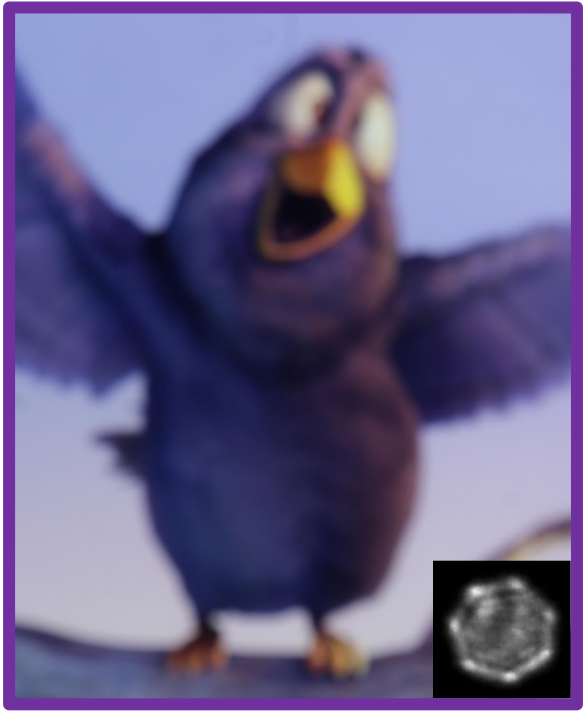


AI

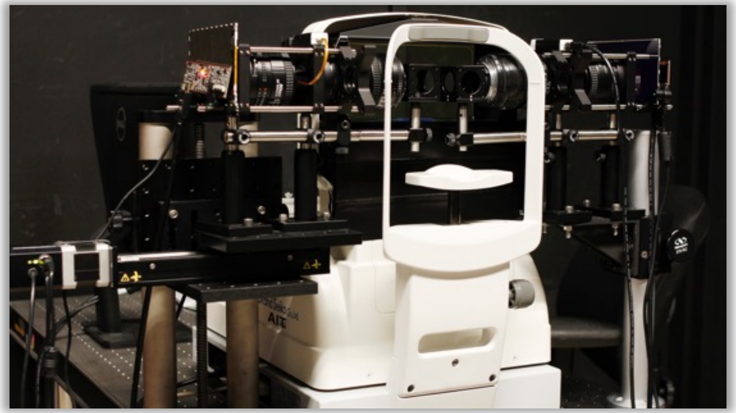


AI @ 3D

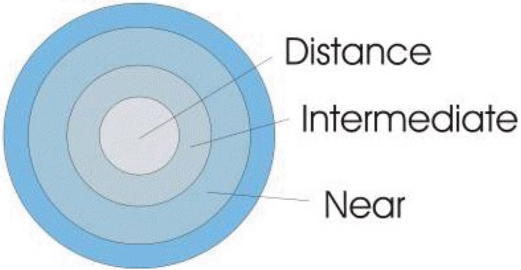
Conventional Display @ 3D



Now: benchtop



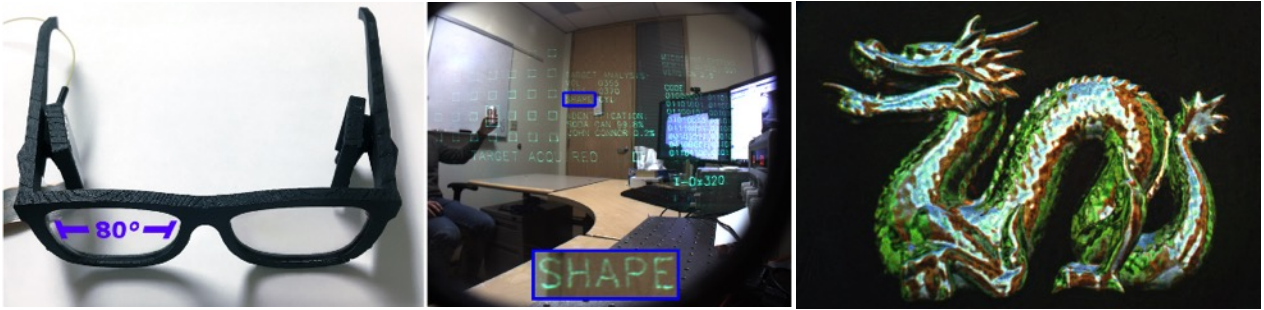
Future: multifocal lenses



5. Holographic Near-eye Displays

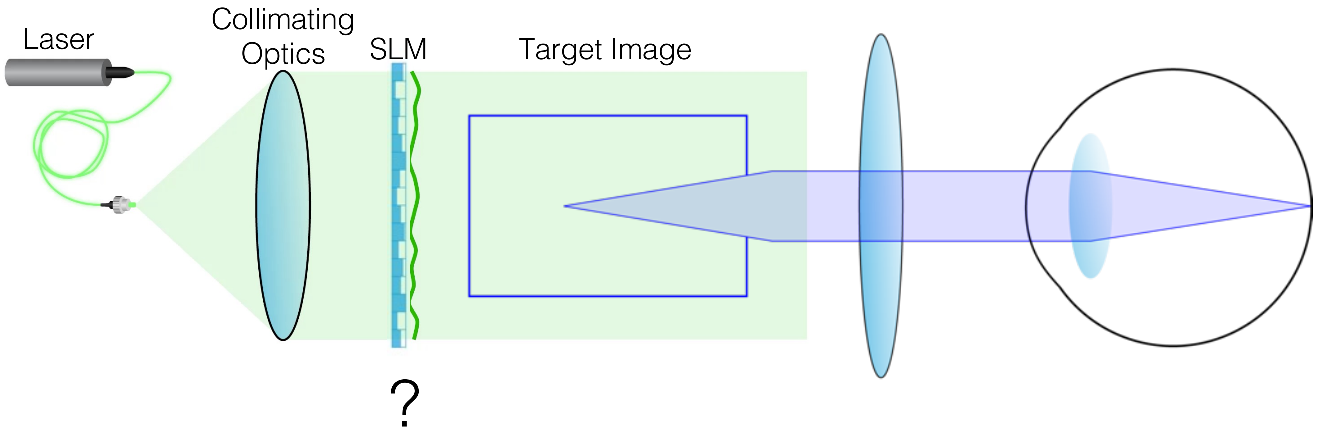
Holographic Near-eye Displays

- recently great image quality demonstrated!
- limited by space-bandwidth product: either small field of view + “large-ish” eyebox or vice versa, but not both
- interference in users’ eyes may be a problem

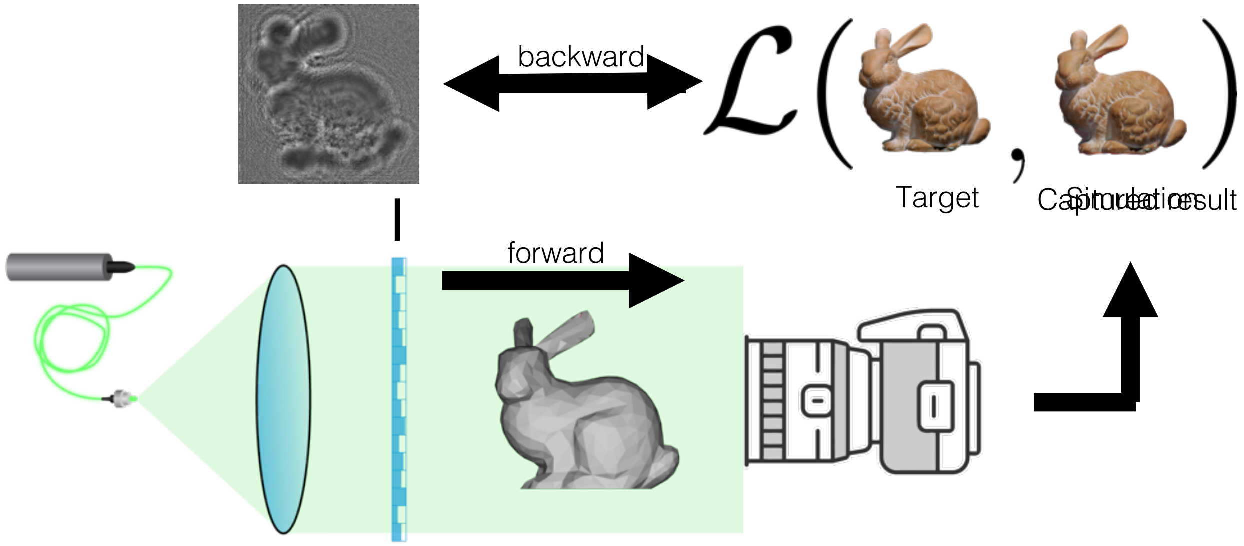


Maimone et al., SIGGRAPH 2017

Holographic Near-eye Displays



Camera-in-the-loop (CITL) Hologram Optimization



[Peng et al., SIGGRAPH Asia 2020]

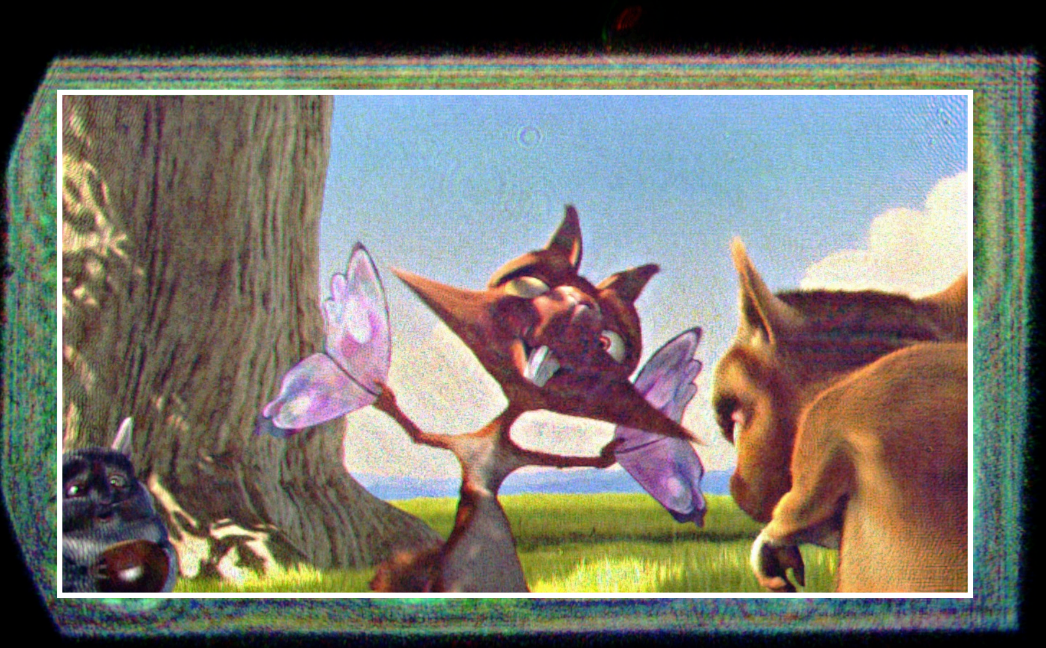
[Peng et al., SIGGRAPH Asia 2020]

Wirtinger Holography

Generated offline
Captured in real-time

[Chakravarthula et al. 2019]

Our Camera-in-the-loop Optimization



Generated offline
Captured in real-time

[Peng et al., SIGGRAPH Asia 2020]

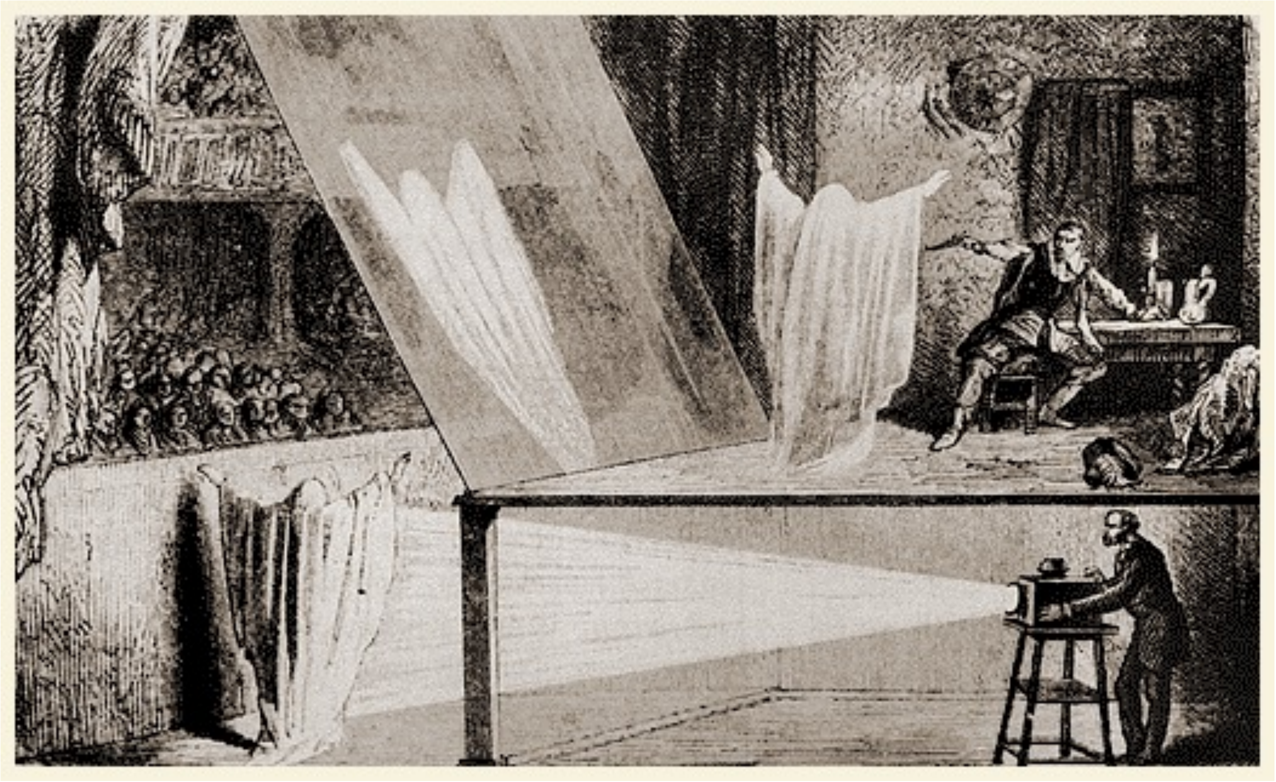
Summary of AR/VR Displays with Focus Cues

- 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 or multiple optically overlaid displays
- Maxwellian-type displays can be interesting, but provide small eyebox
- light field and holographic displays may be “ultimate” displays in the longer-run → need to solve a few “issues” first

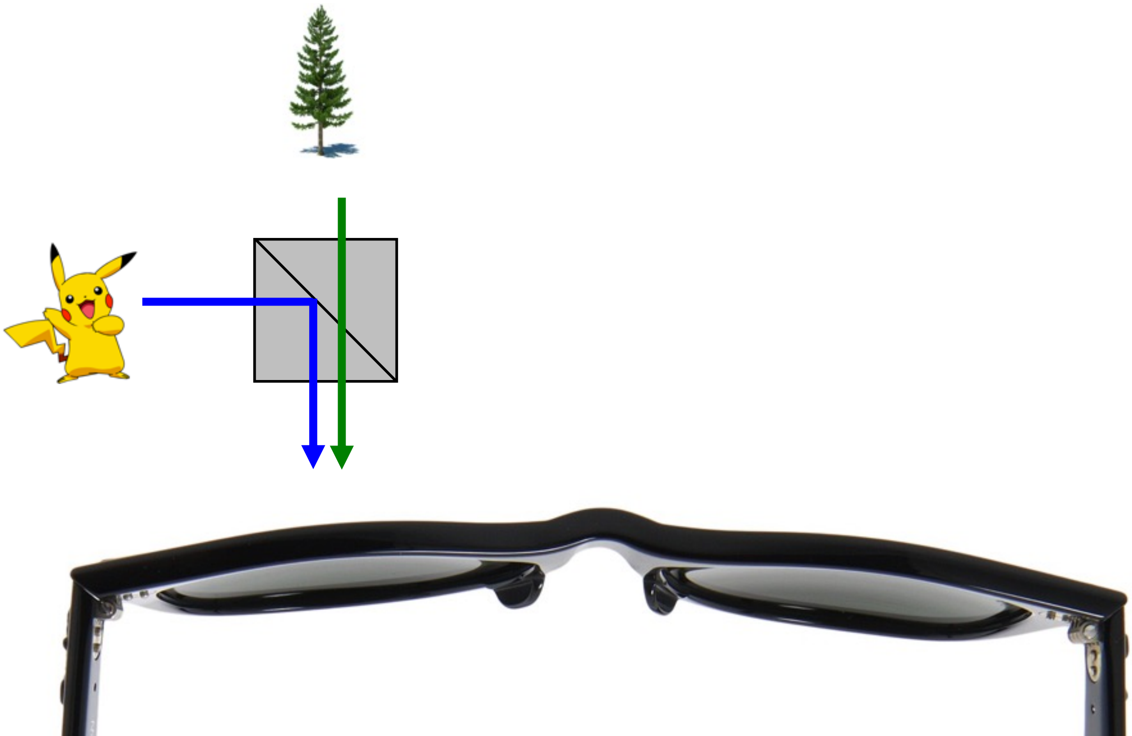
Overview of Optical See-through AR Displays

Ray Ban

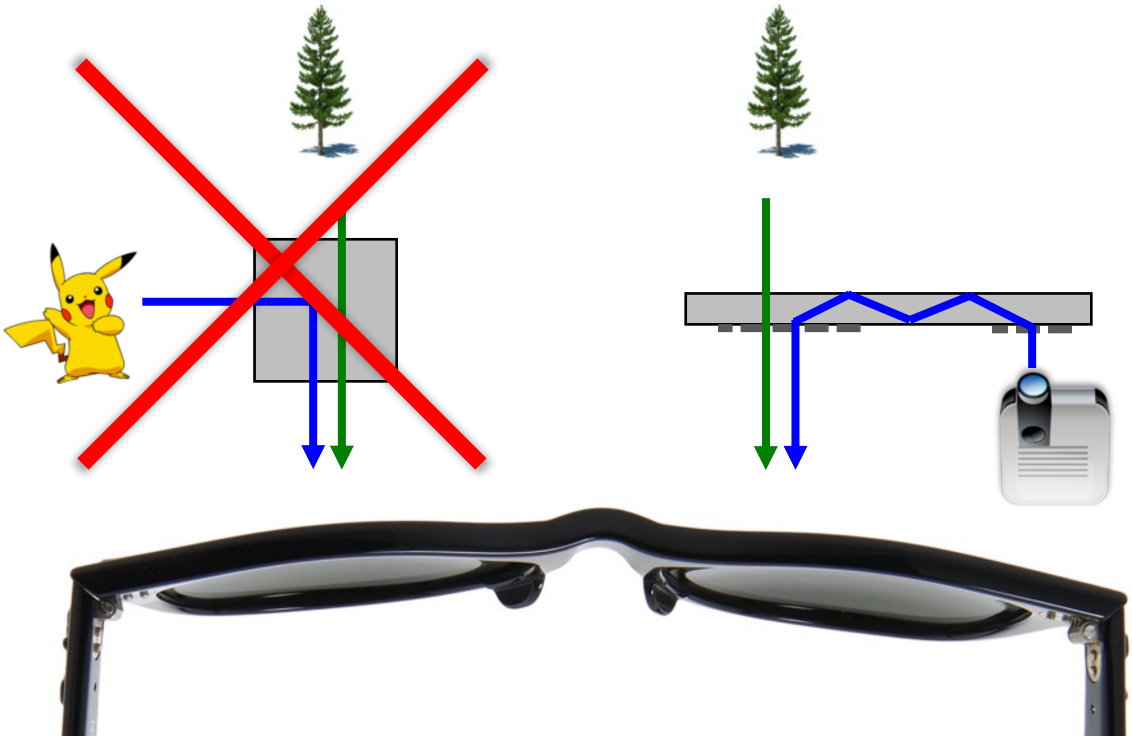
Pepper’s Ghost 1862



Thin Beam Combiner?

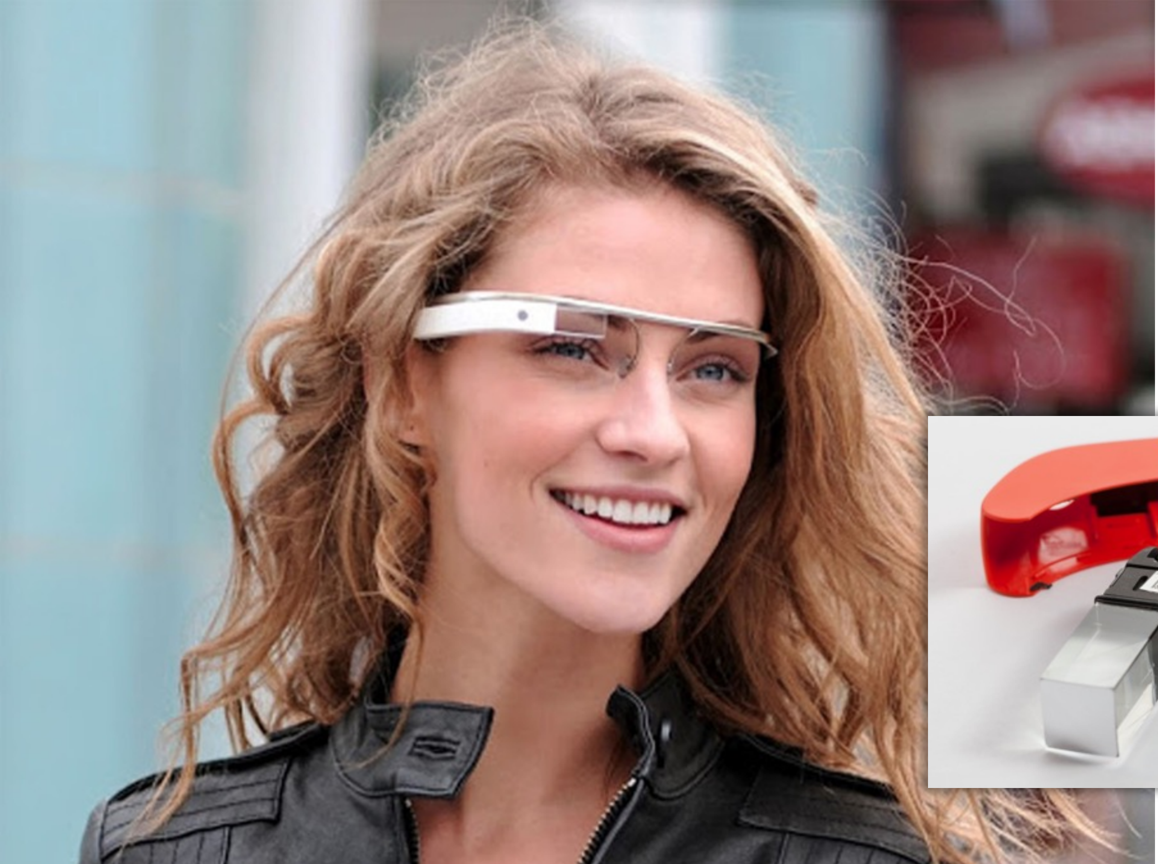


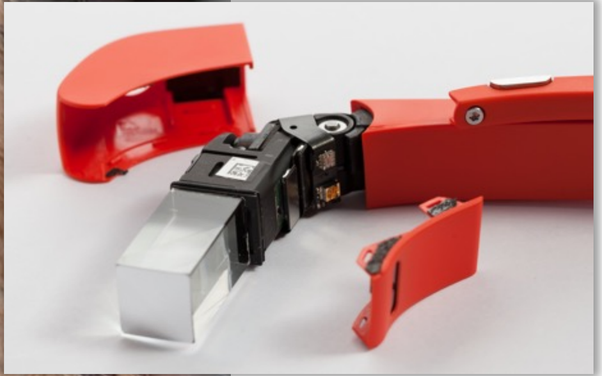
Thin Beam Combiner!



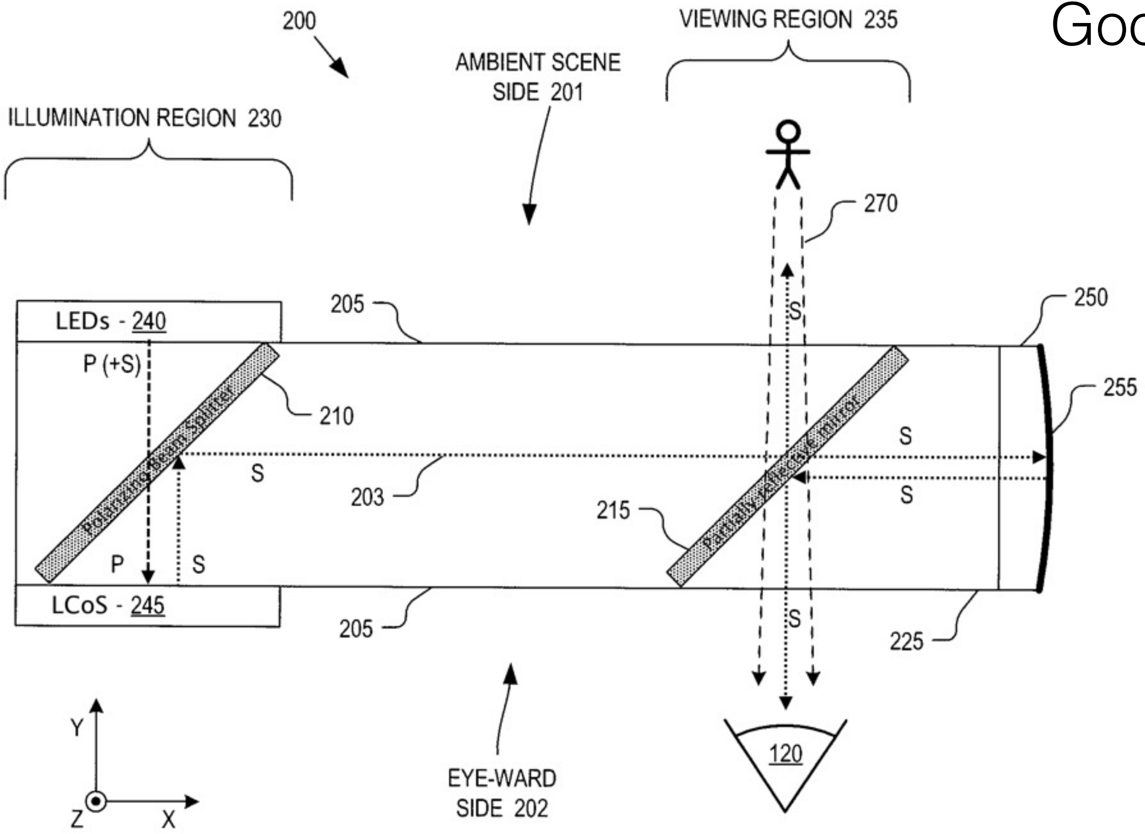
OST AR - Case Studies

Google Glass





Google Glass



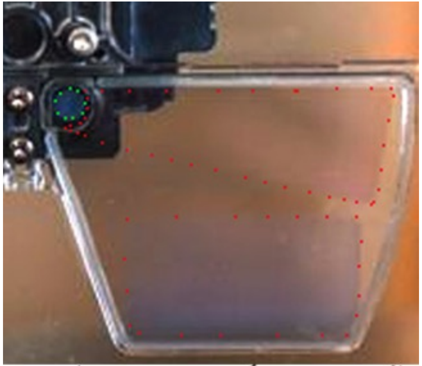
Meta 2

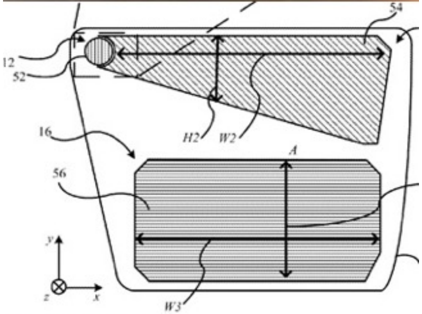
- larger field of view (90 deg) than Glass
- also larger device form factor

Microsoft HoloLens

Microsoft HoloLens

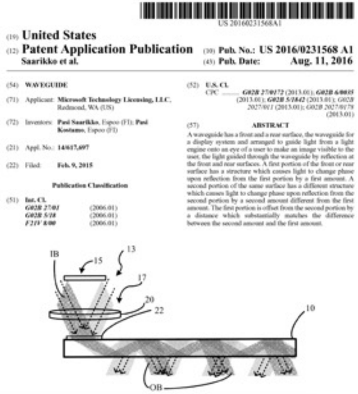
- diffraction grating
- small FOV (30x17), but very good image quality





US 2016/0231568

Fig. 3B


(19) United States
(12) Patent Application Publication
Saarikko et al.
(10) Pub. No.: US 2016/0231568 A1
(43) Pub. Date: Aug. 11, 2016

(54) WAVEGUIDE

(71) Applicant: Microsoft Technology Licensing, LLC, Redmond, WA (US)

(72) Inventors: Pasi Saarikko, Espoo (FI); Pasi Kostamo, Espoo (FI)

(21) Appl. No.: 14/617,697

(22) Filed: Feb. 9, 2015

Publication Classification

(51) Int. Cl.
G02B 27/01 (2006.01)
G02B 5/18 (2006.01)
F21V 8/00 (2006.01)

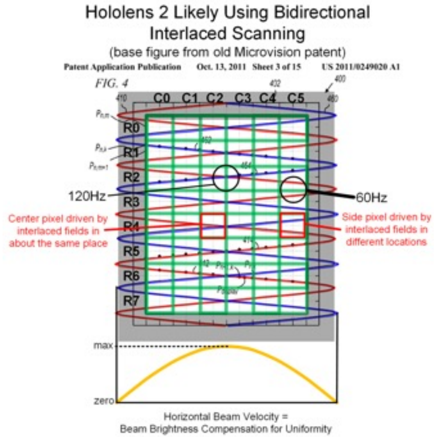
(52) U.S. Cl.
CPC G02B 27/0172 (2013.01); G02B 6/0035 (2013.01); G02B 5/1842 (2013.01); G02B 2027/011 (2013.01); G02B 2027/0178 (2013.01)

(57) ABSTRACT

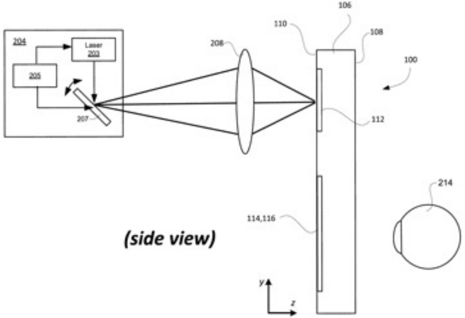
A waveguide has a front and a rear surface, the waveguide for a display system and arranged to guide light from a light engine onto an eye of a user to make an image visible to the user, the light guided through the waveguide by reflection at the front and rear surfaces. A first portion of the front or rear surface has a structure which causes light to change phase upon reflection from the first portion by a first amount. A second portion of the same surface has a different structure which causes light to change phase upon reflection from the second portion by a second amount different from the first amount. The first portion is offset from the second portion by a distance which substantially matches the difference between the second amount and the first amount.

Microsoft HoloLens 2

- laser-scanned waveguide display
- claimed 2K resolution per eye (2560x1440), probably via “interlaced” scanning
- field of view: 52° diagonally (3:2 aspect, 47 pixels per visual degree)

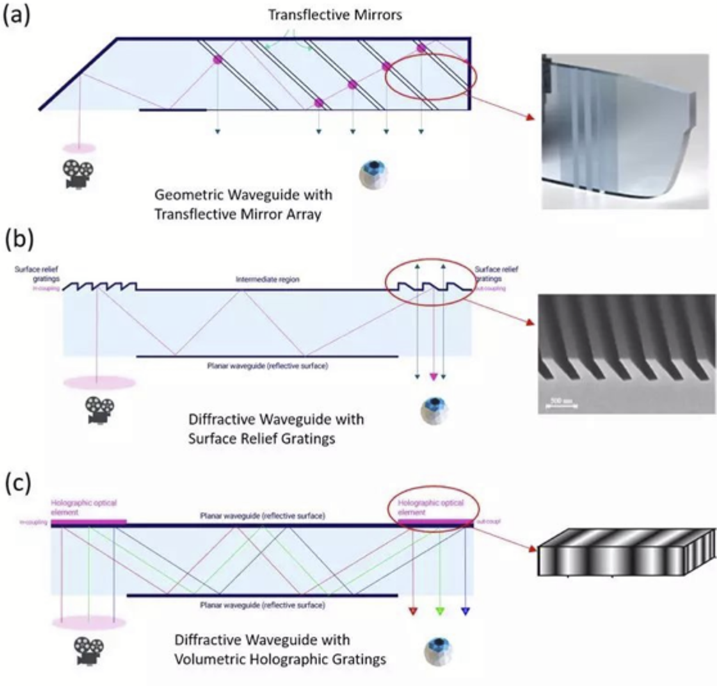


https://www.kguttag.com/2019/02/27/hololens-2-first-impressions-good-ergonomics-but-the-lbs-resolution-math-fails/



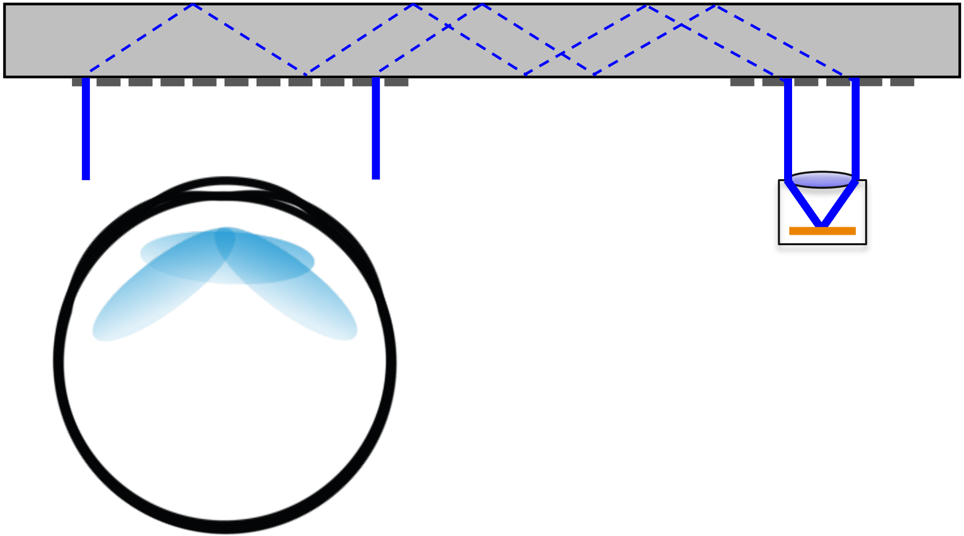
Wall et al. US 10,025,093 2018

AR Lightguides and Waveguides

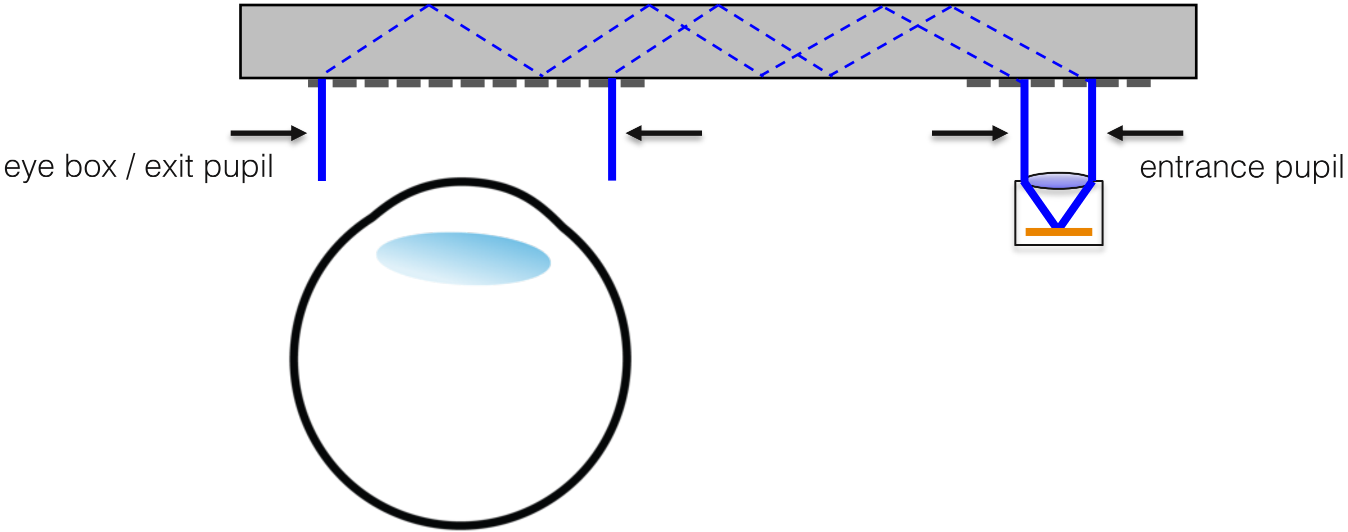


https://arvrjourney.com/understanding-waveguide-the-key-technology-for-augmented-reality-near-eye-display-part-ii-fe4bf3490fa

Challenges: Eye Box vs Field of View

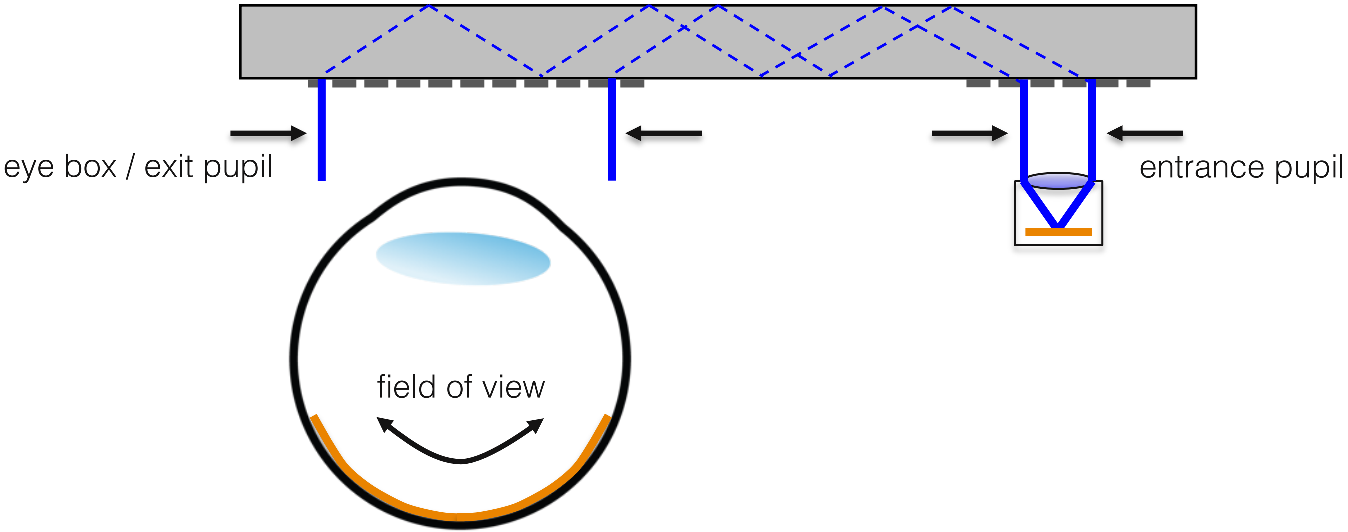


Challenges: Eye Box vs Field of View



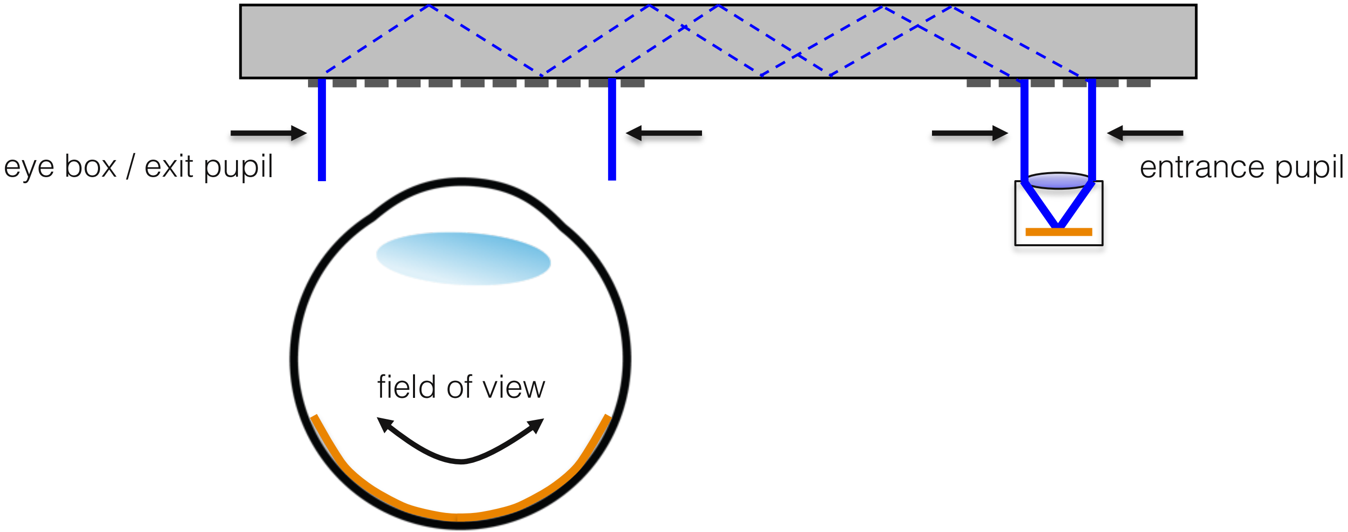
- need small entrance pupil (small device) and large exit pupil (large eye box) - pupil needs to be magnified

Challenges: Eye Box vs Field of View



- need small display (small device) but large field of view – image needs to be magnified

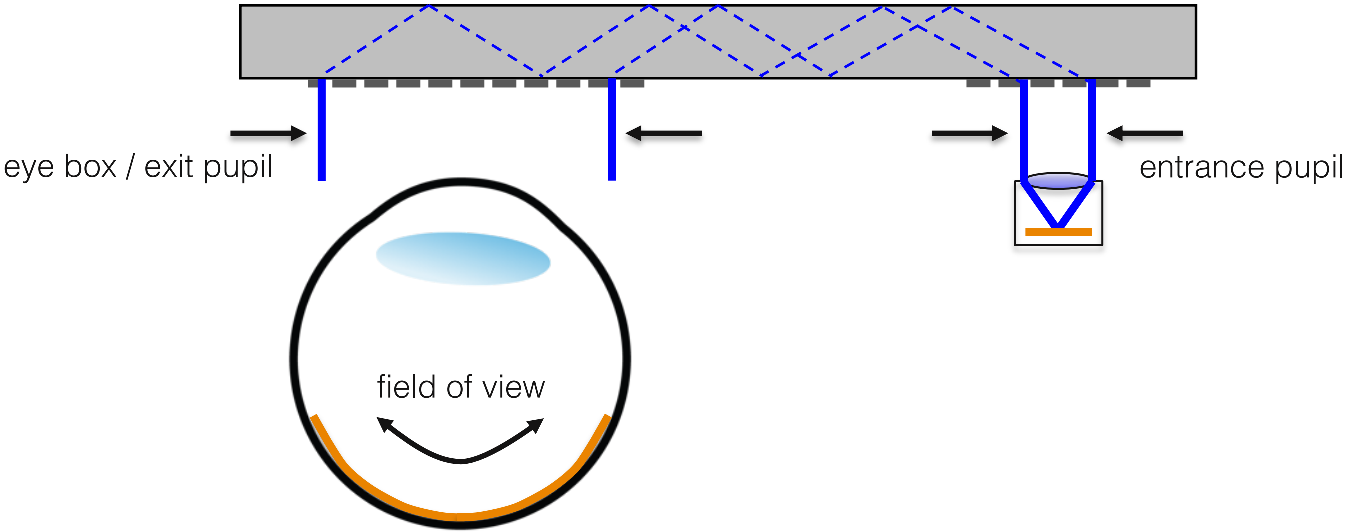
Challenges: Eye Box vs Field of View



- pupil needs to be magnified
- image needs to be magnified

can't get both at the same time – etendue!

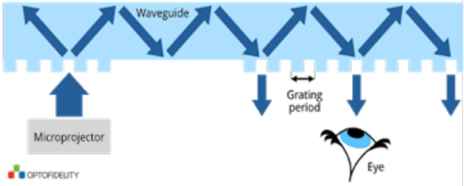
Challenges: Eye Box vs Field of View



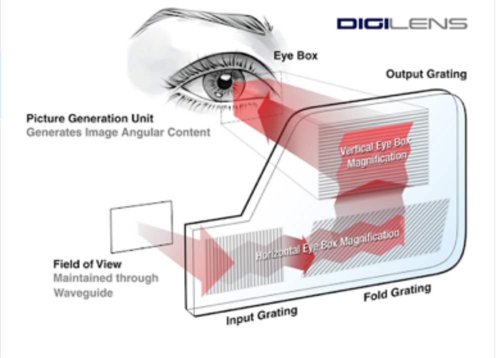
- possible solutions: exit pupil replication (loss of light), live with small FOV (not great), dynamically steer eye box (mechanically difficult), ..

Exit Pupil Expansion

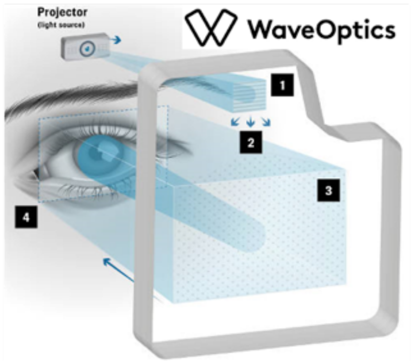
(a) 1D Pupil Expansion



(b) 2D Pupil Expansion with Turn Grating

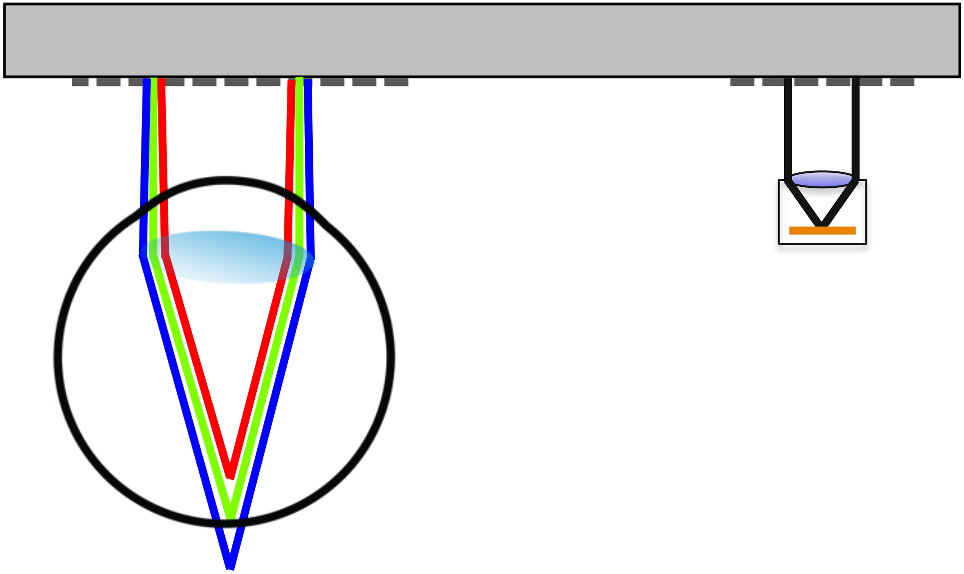


(c) 2D Pupil Expansion with 2D Grating



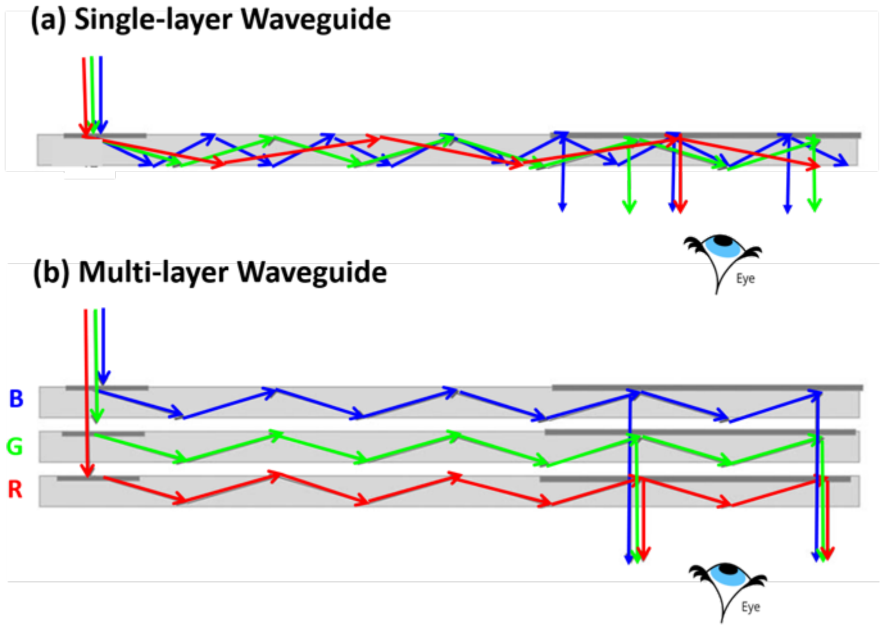
https://arvrjourney.com/understanding-waveguide-the-key-technology-for-augmented-reality-near-eye-display-part-ii-fe4bf3490fa

Challenges: Chromatic Aberrations



- thin grating couplers create chromatic aberrations

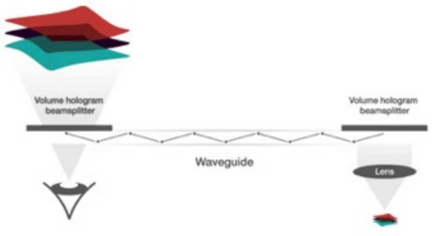
Challenges: Chromatic Aberrations



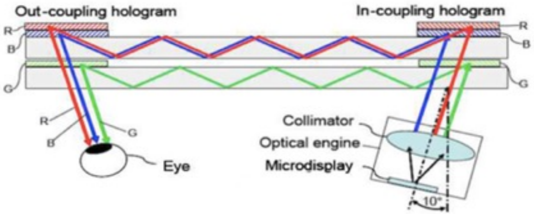
https://arvrjourney.com/understanding-waveguide-the-key-technology-for-augmented-reality-near-eye-display-part-ii-fe4bf3490fa

Challenges: Chromatic Aberrations

volume holographic couplers,
e.g. TruLife Optics

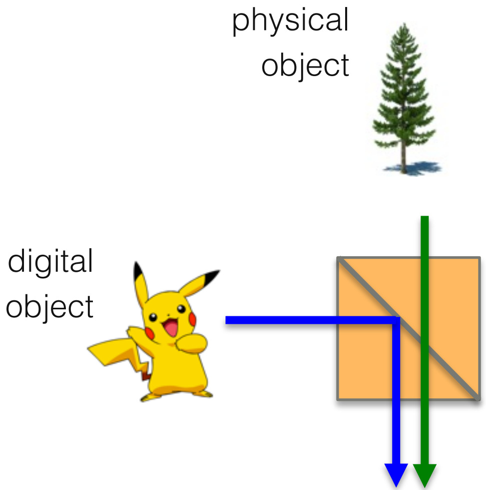


stacked waveguides



- all solutions have their own problems: ease of manufacturing, yield, robustness, cost, …

Occlusions



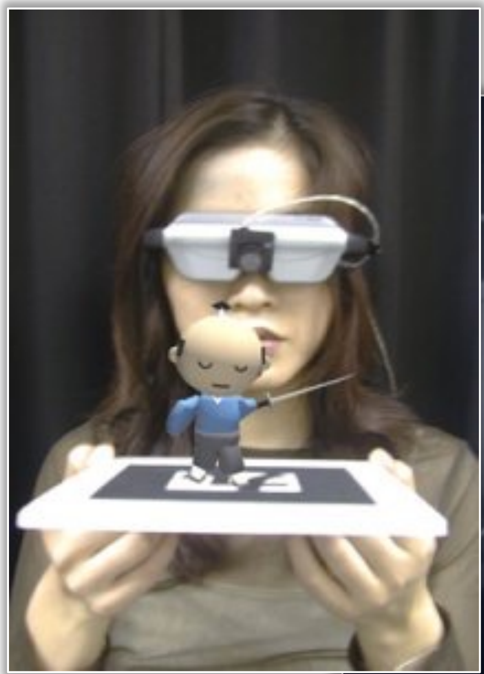
Case 1:
digital in front of physical

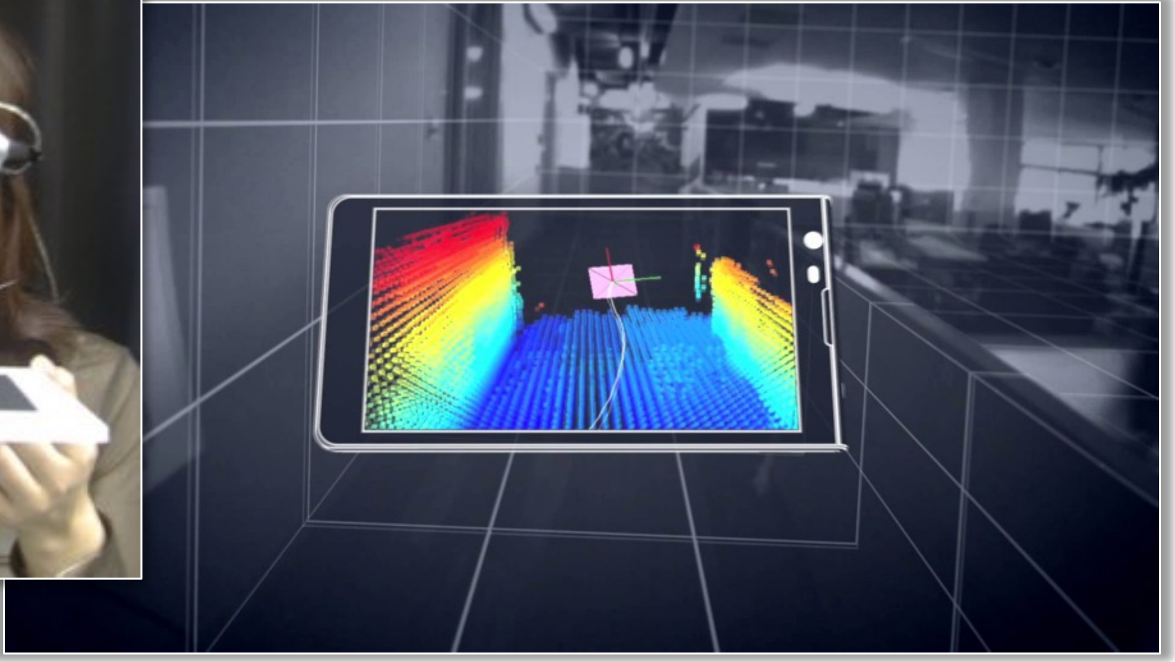
→ <u>difficult</u>: need to block real light!

Case 2:
physical in front of digital

→ <u>easy</u>: don't render digital object everywhere

Video-based AR: ARCore, ARKit, ARToolKit, …





Next Lecture: Inertial Measurement Units I

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