Computational Near-eye Displays

with Focus Cues

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TU Vienna Seminar

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STANFORD COMPUTATIONAL IMAGING LAB

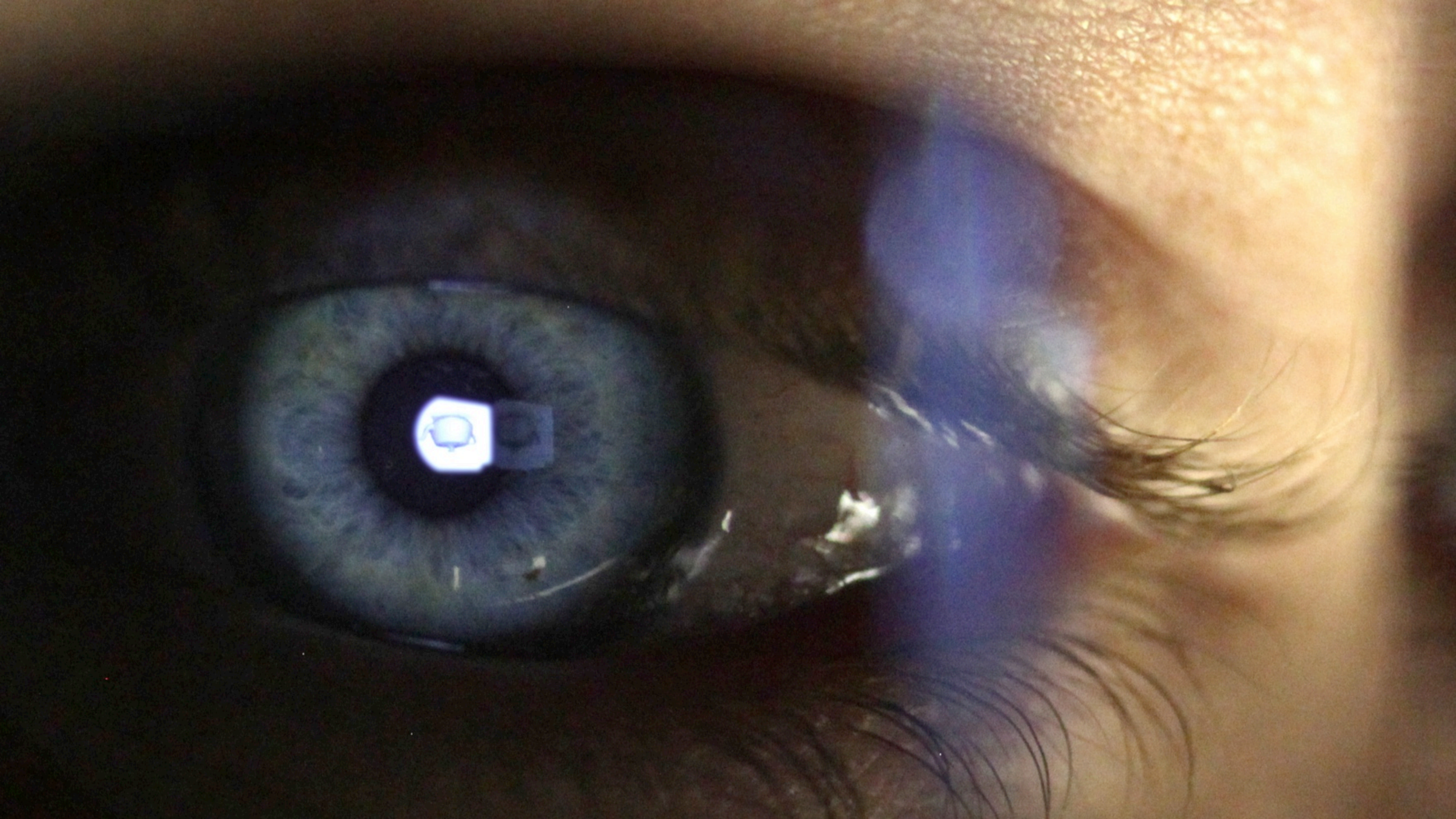
www.computationalimaging.org

vir·tu·al re·al·i·ty

vərCH(əw)əl rēˈalədē

the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors.

VPL Research



simulation & training

visualization & entertainment

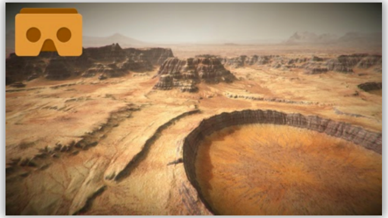
remote control of vehicles, e.g. drones

gaming

robotic surgery

architecture walkthroughs

education



virtual travel

a trip down the rabbit hole

VR at Stanford's Medical School

photo from Stanford Medicine News

- Lucile Packard Children's Hospital: used to alleviate pain, anxiety for pediatric patients
- VR Technology Clinic: applications in psychotherapy, mental health, for people with phantom pain, …
- help train residents, assist surgeons planning operations, …

National Academy of Engineering

"Enhance Virtual Reality" is 1 of 14 NAE grand challenges for engineering in the 21st century

image from NAE

Exciting Engineering Aspects of VR/AR

- cloud computing
- shared experiences

- CPU, GPU
- IPU, DPU?

- sensors & imaging
- computer vision
- scene understanding

- compression, streaming

- VR cameras

- photonics / waveguides
- human perception
- displays: visual, auditory, vestibular, haptic, …

- HCI
- applications

images by microsoft, facebook

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images by microsoft, facebook

Where We Want It To Be

image by ray ban

Personal Computer
e.g. Commodore PET 1983

Laptop
e.g. Apple MacBook

Smartphone
e.g. Google Pixel

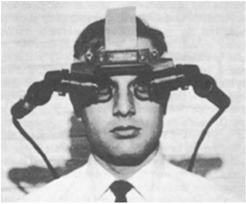
AR/VR
e.g. Microsoft Hololens

???

A Brief History of Virtual Reality

Stereoscopes
Wheatstone, Brewster, …

VR & AR
Ivan Sutherland



Nintendo Virtual Boy

VR explosion
Oculus, Sony, HTC, MS, …

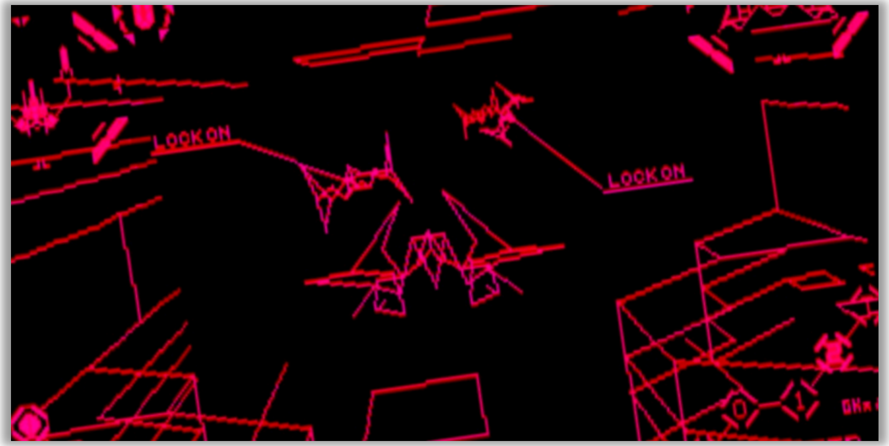
Ivan Sutherland’s HMD

- optical see-through AR, including:
    - displays (2x 1” CRTs)
    - rendering
    - head tracking
    - interaction
    - model generation
- computer graphics
- human-computer interaction

I. Sutherland “A head-mounted three-dimensional display”, Fall Joint Computer Conference 1968

Nintendo Virtual Boy

- computer graphics & GPUs were not ready yet!

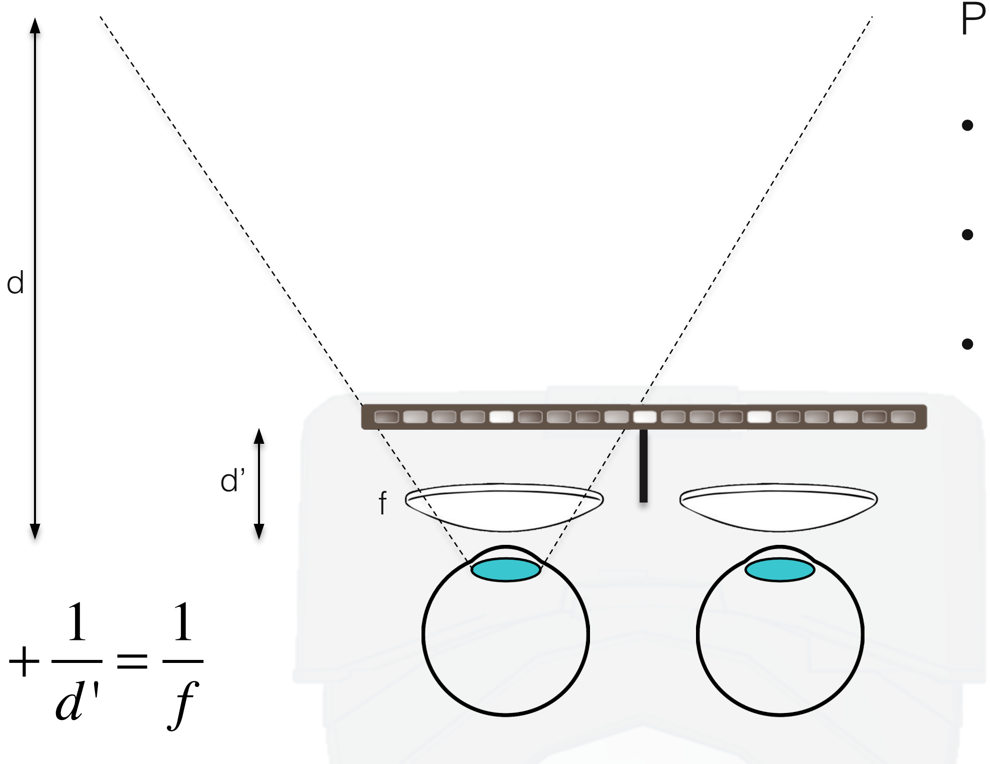


Game: Red Alarm

Where we are now

IFIXIT teardown

Virtual Image



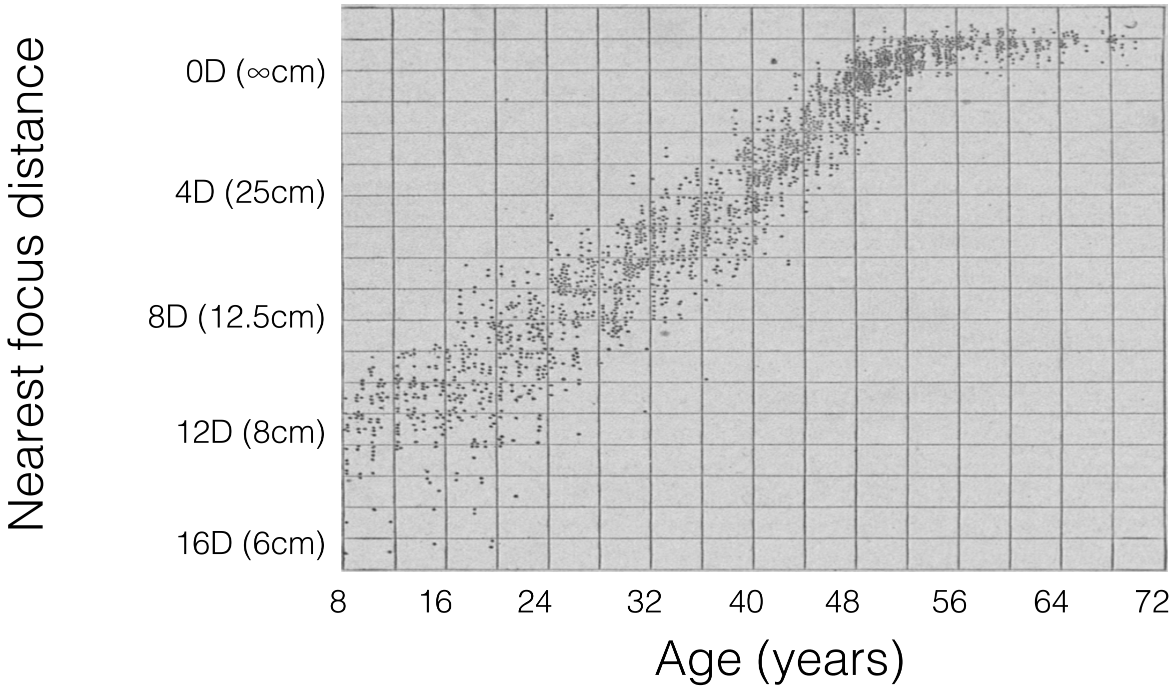
$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{f}$$

Problems:

- fixed focal plane
- no focus cues ☹
- cannot drive accommodation with rendering!

Focus Cues – An Important Depth Cue

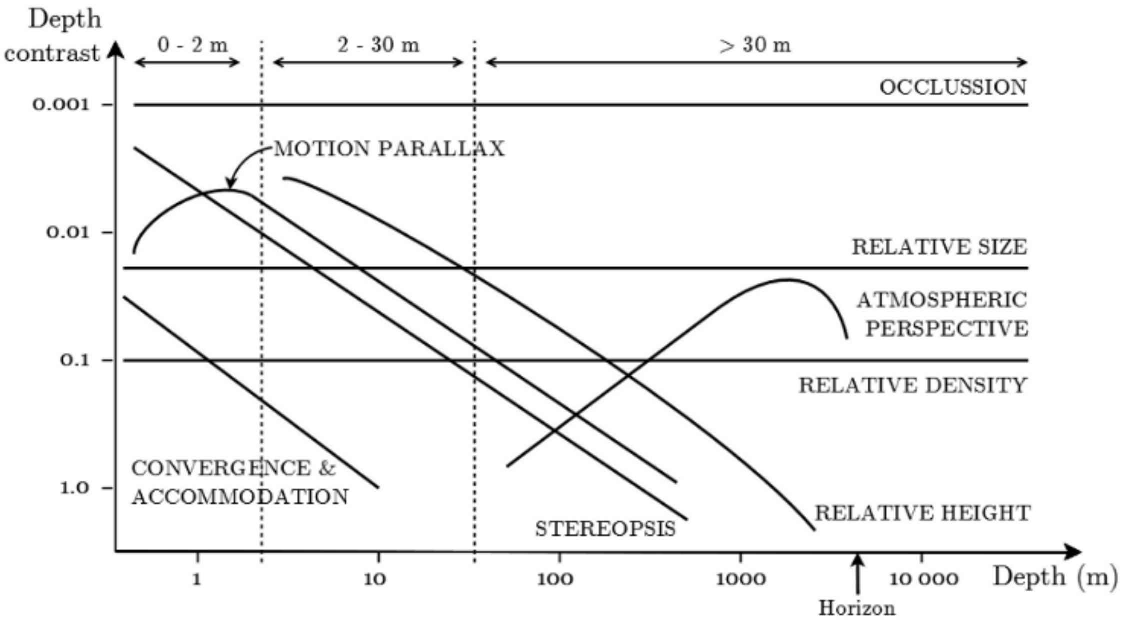
Importance of Focus Cues Decreases with Age - Presbyopia

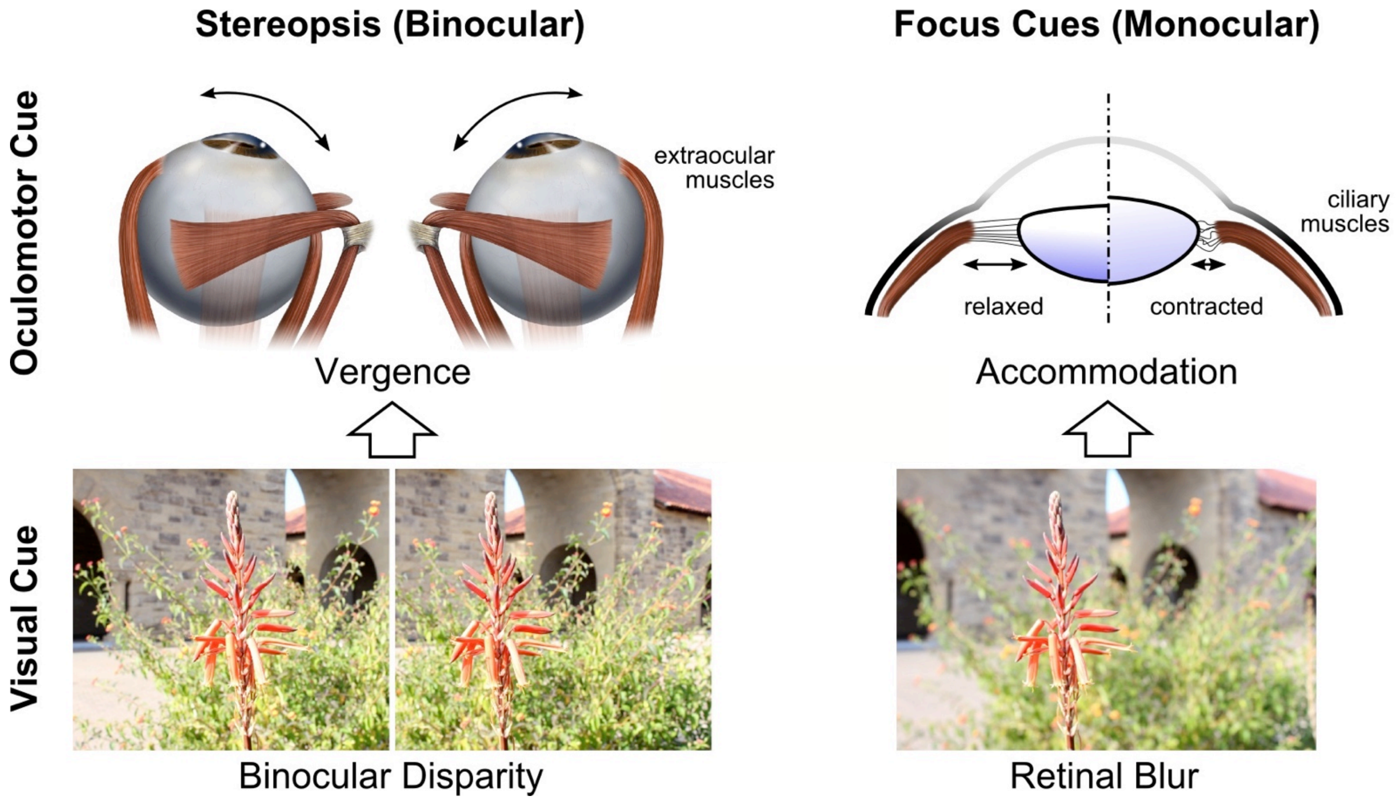


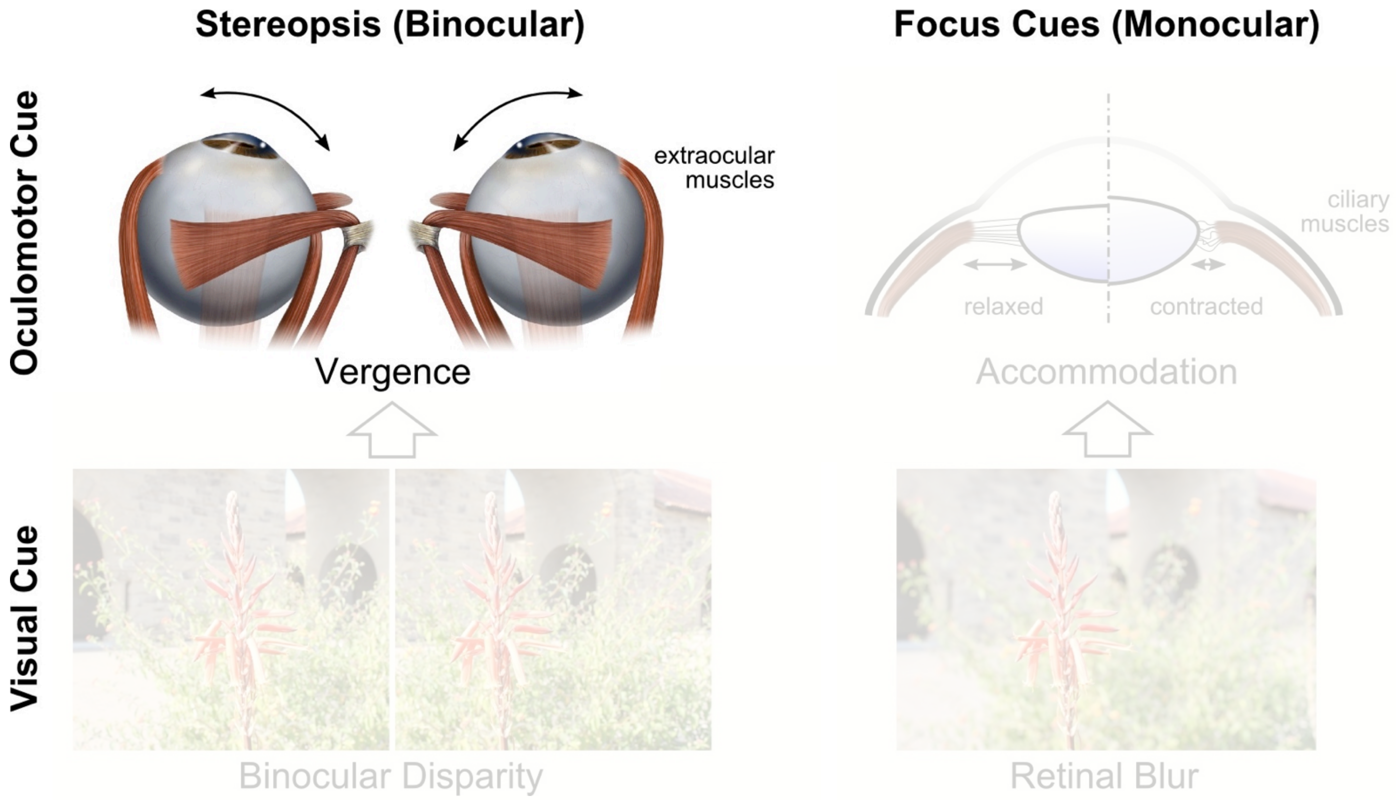
Duane, 1912

Relative Importance of Depth Cues

Cutting & Vishton, 1995




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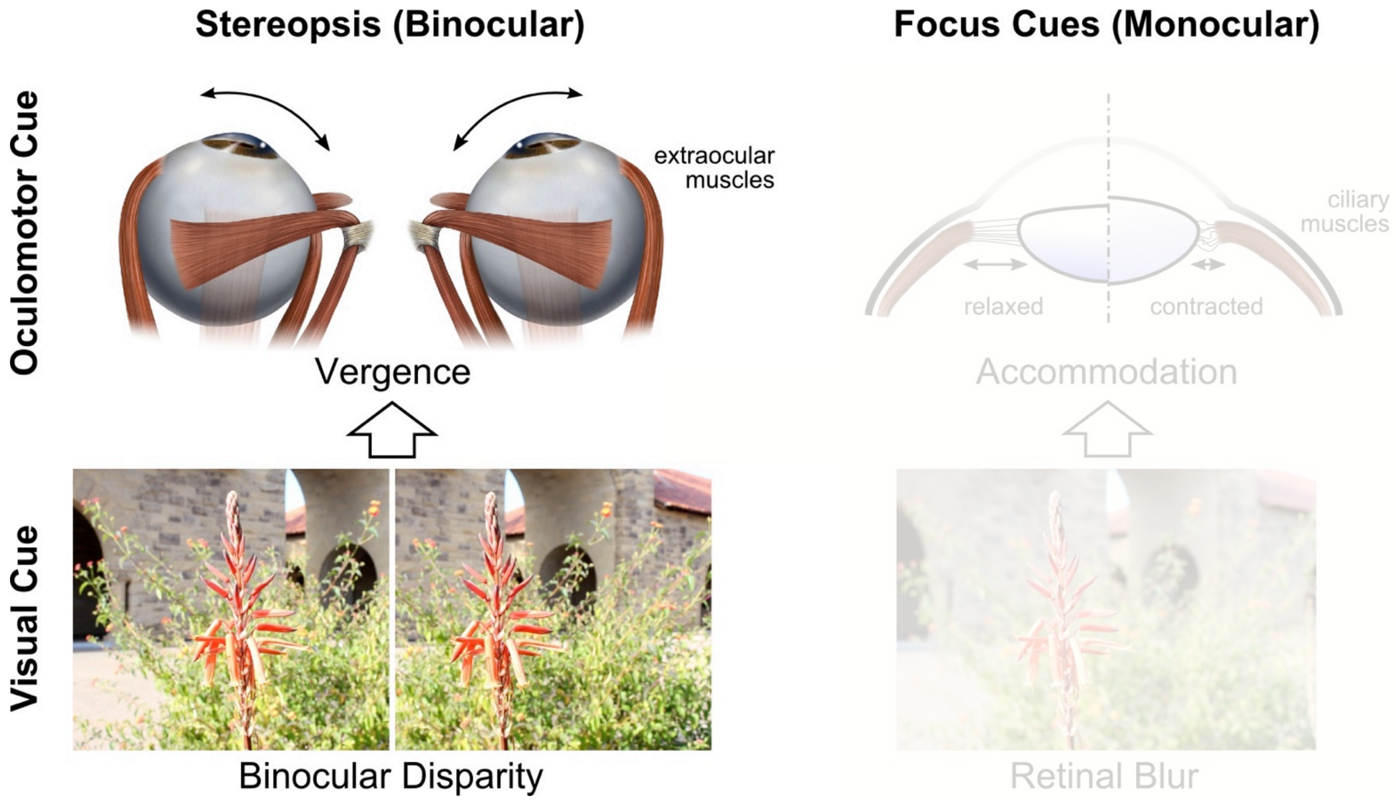
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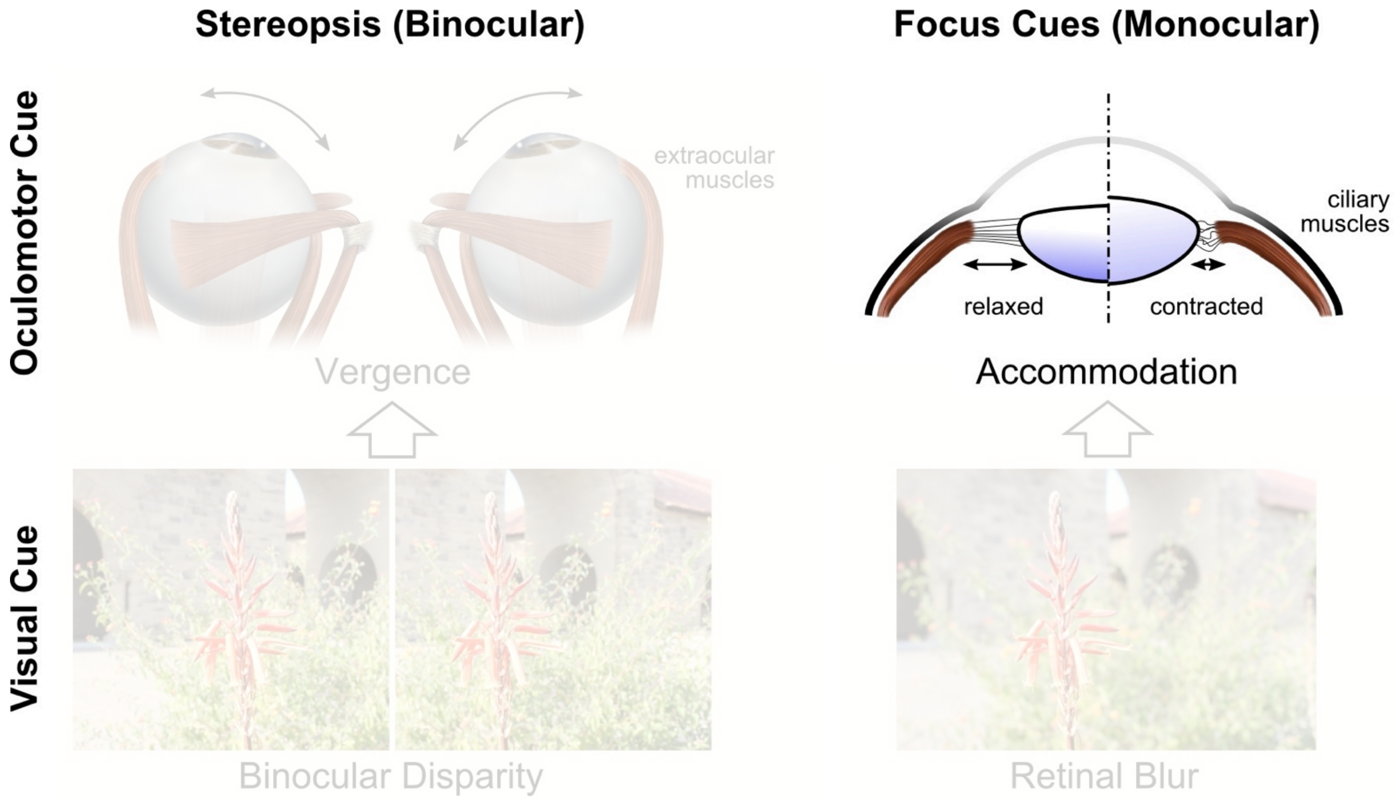
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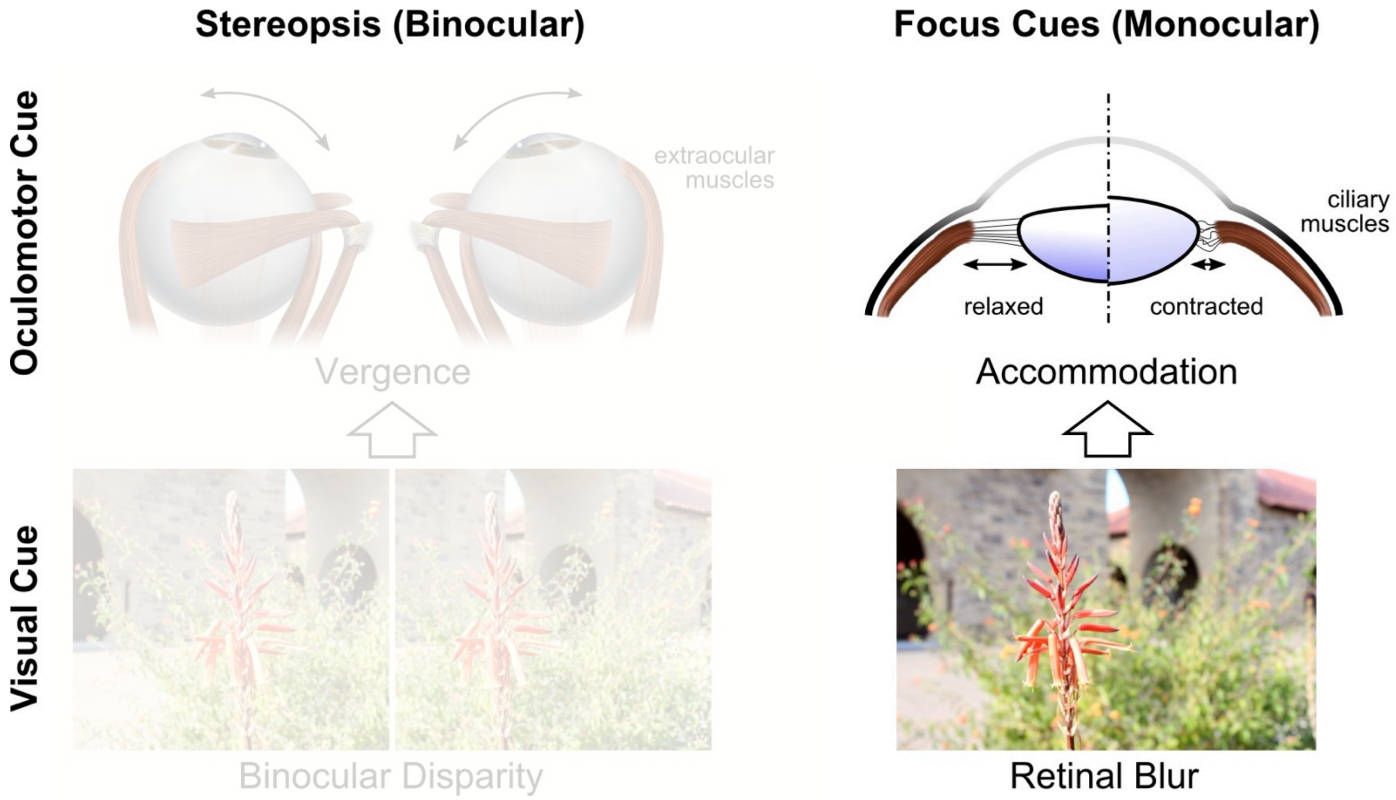
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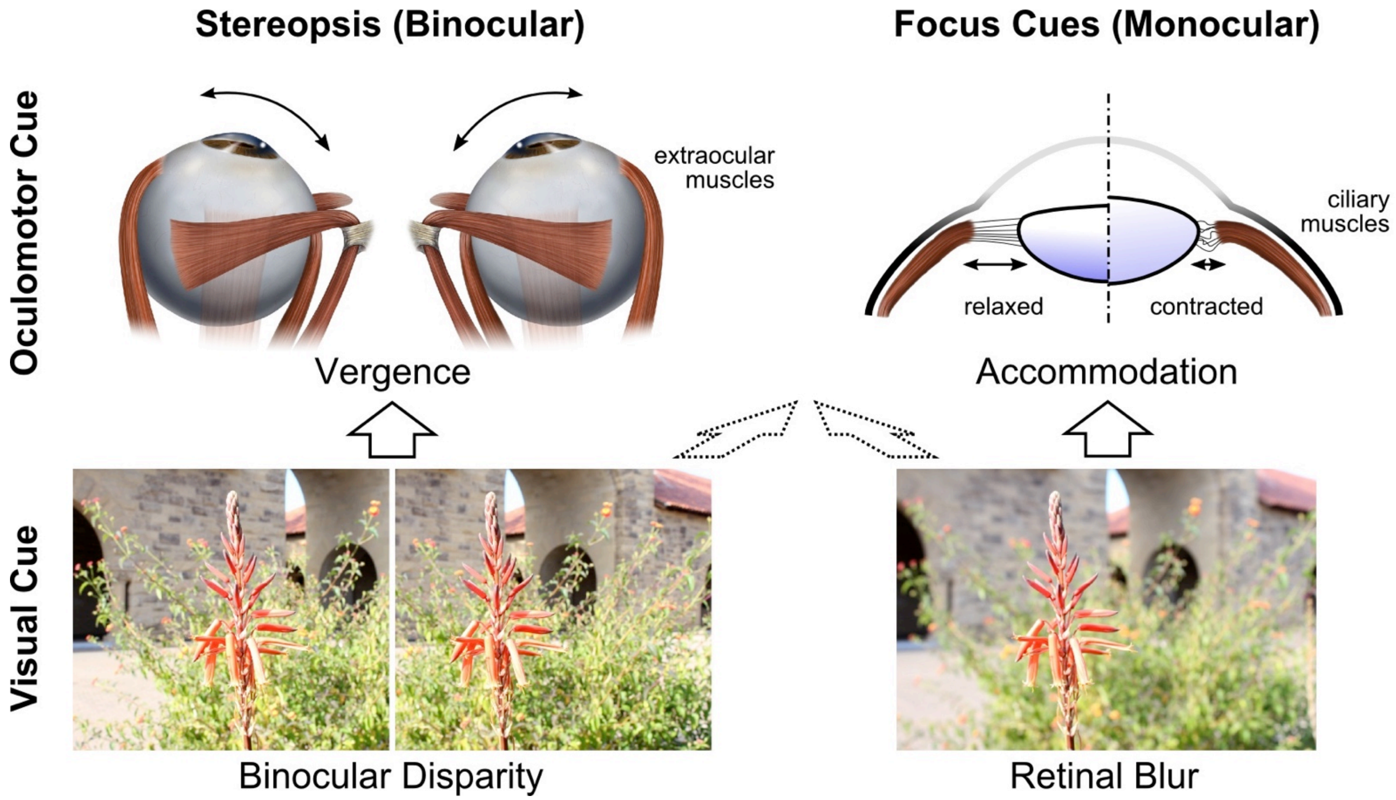
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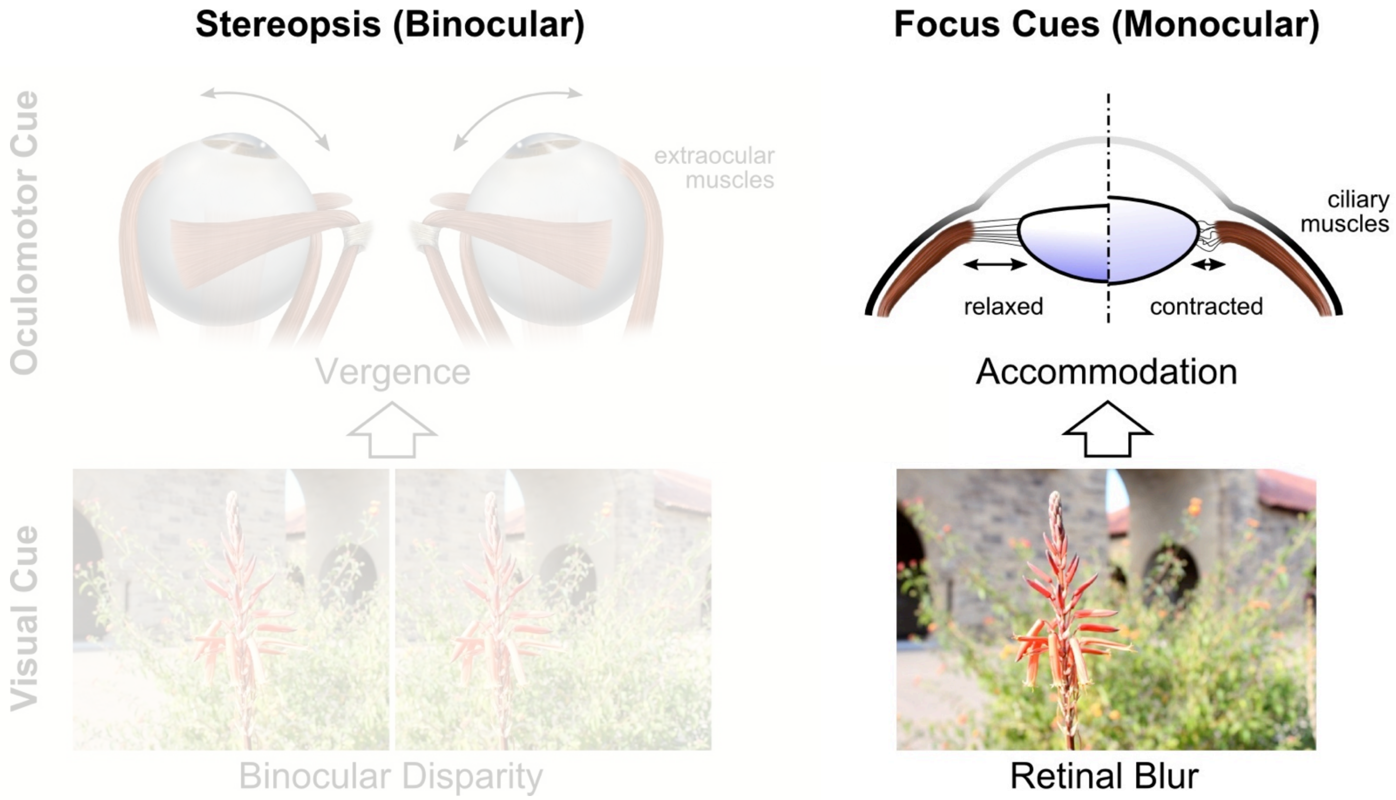
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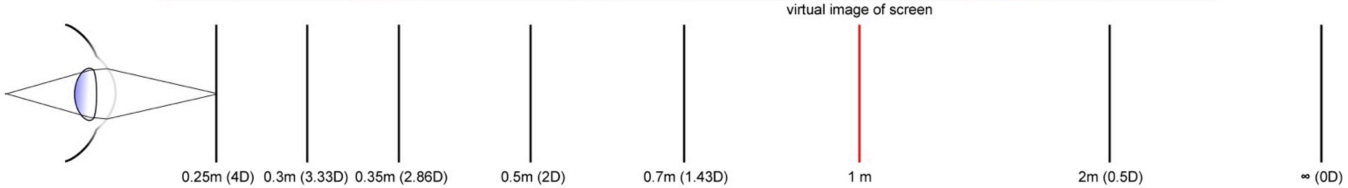
Retinal Blur

Blur Gradient Driven Accommodation

Conventional Display



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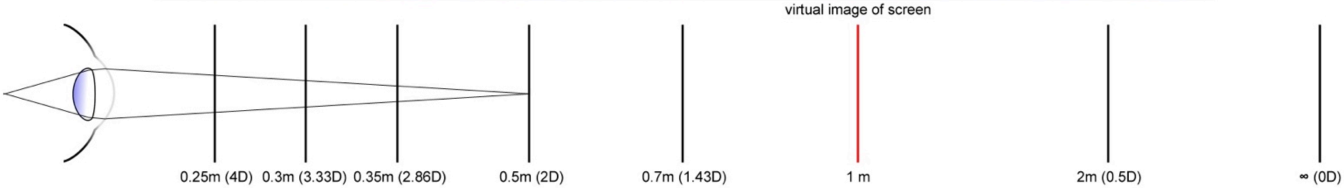

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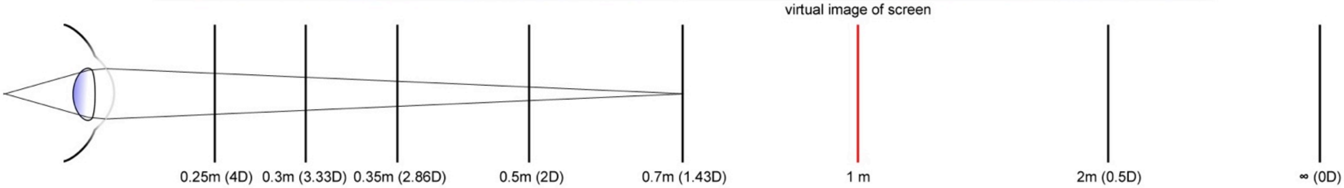

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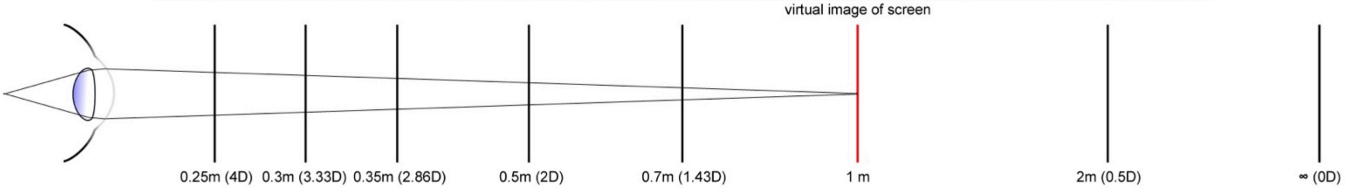

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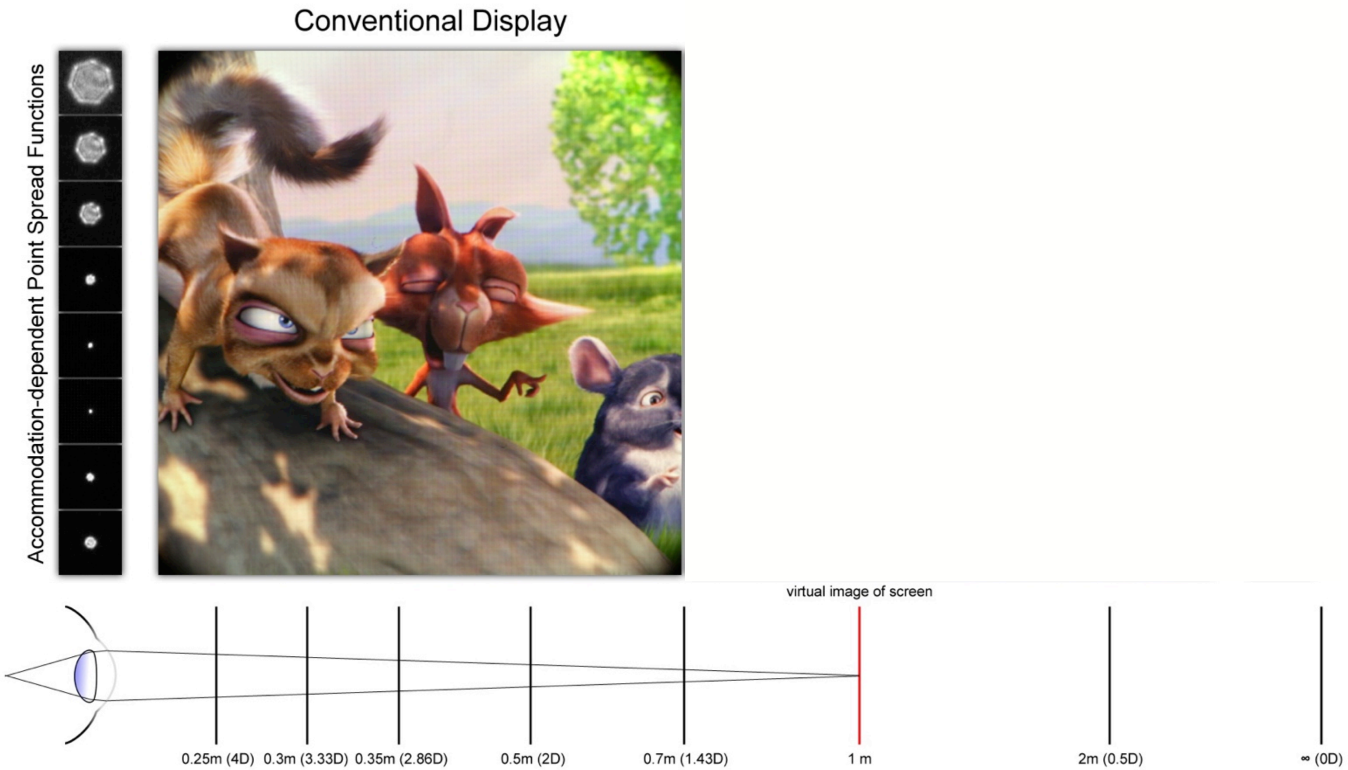
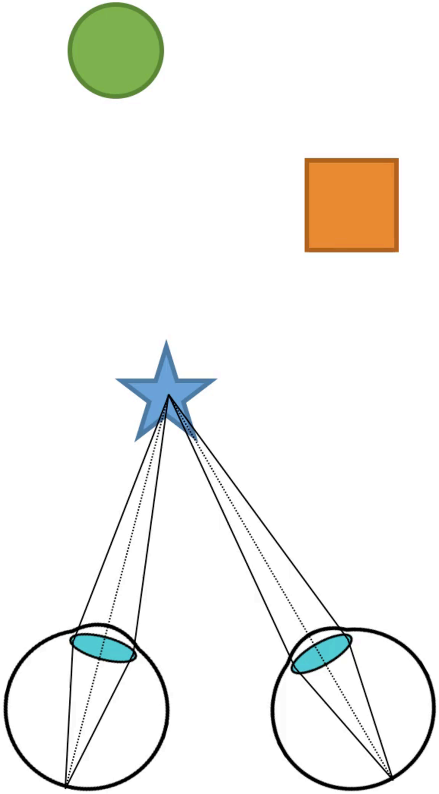
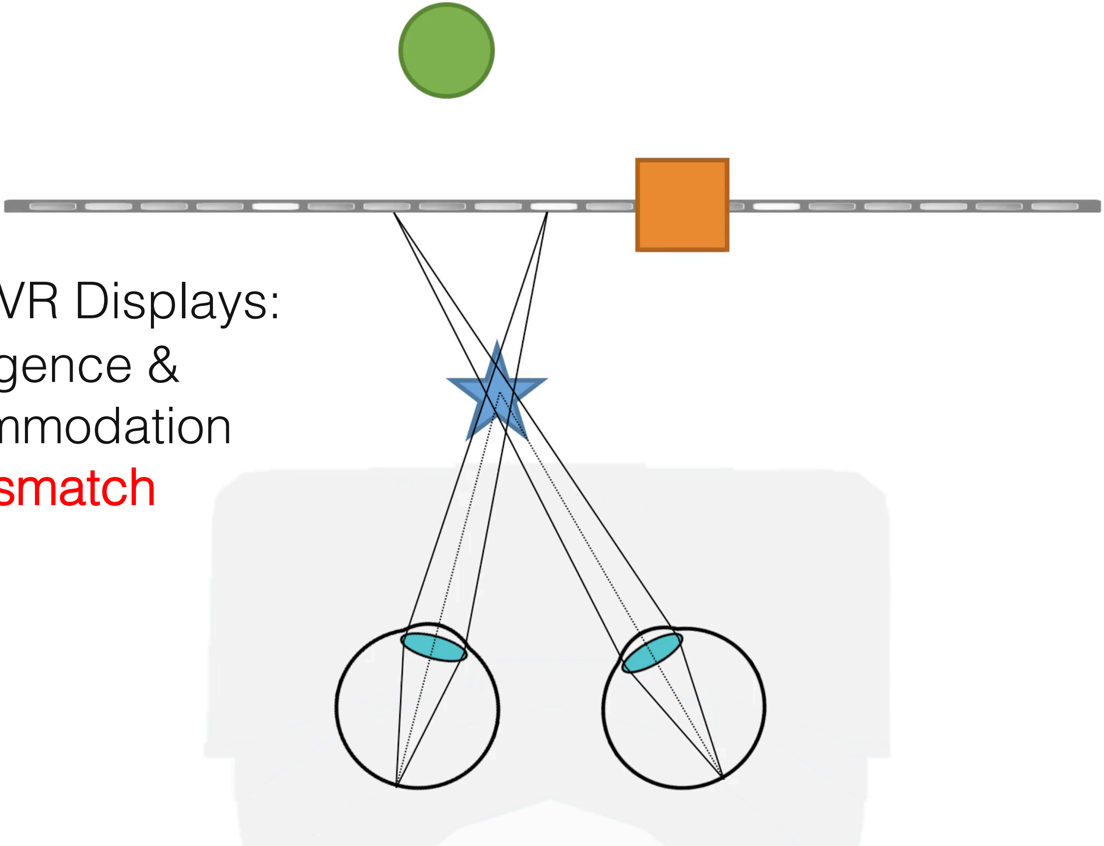


The Vergence-Accommodation Conflict (VAC)

Real World:
Vergence &
Accommodation
Match!



Current VR Displays:
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)
- also: double vision (diplopia), reduced visual clarity, possibly nausea

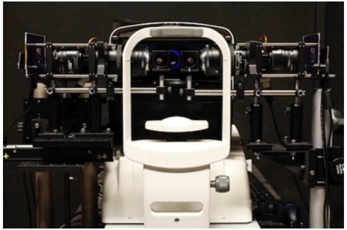
- Q1: How to address the vergence-accommodation conflict for users of different ages?

- Q2: Can computational displays effectively replace glasses in VR/AR?

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

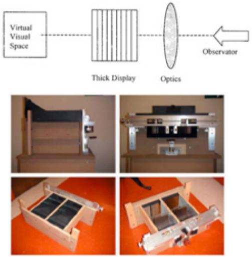
possible solutions: gaze-contingent focus, light fields, …

1. Varifocal Displays



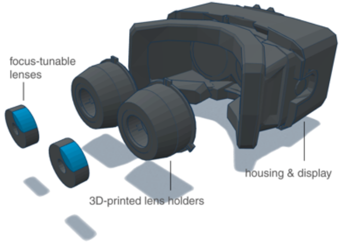
Sugihara et al., SID 1998
Liu et al., ISMAR 2008
Koulieris et al.,SIGGRAPH 2017
Padmanaban et al., PNAS 2017 …

2. Multiplane Displays



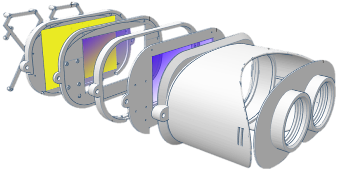
Rolland et al., Applied Optics 2000
Akeley et al., SIGGRAPH 2004 …

3. Monovision Displays



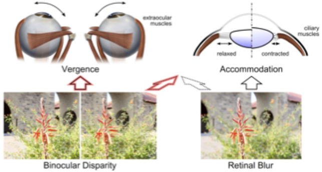
Konrad et al., SIGCHI 2016
Johnson et al., Optics Express 2016 …

4. Light Field



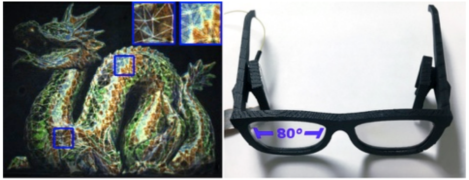
Huang et al., SIGGRAPH 2015
Lanman et al., SIGGRAPH Asia 2013 …

5. Accommodation-invariant Displays



Konrad et al., SIGGRAPH 2017

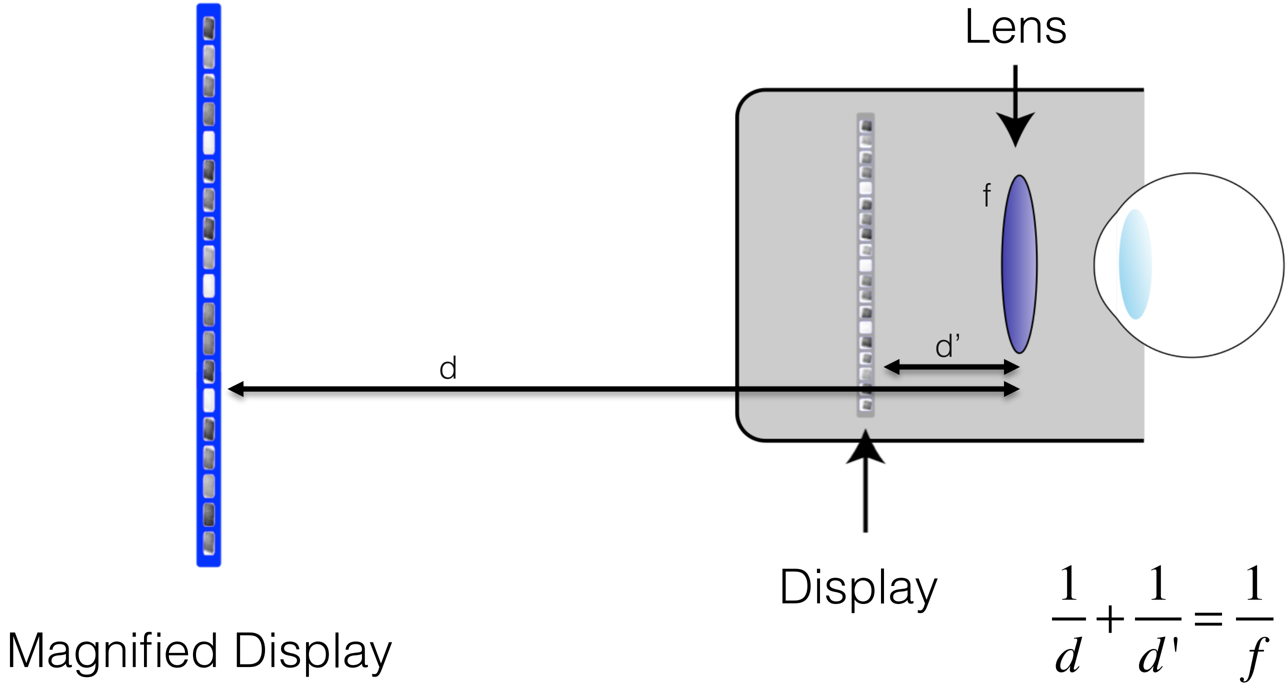
Holographic Displays



Maimone et al., SIGGRAPH 2017
…

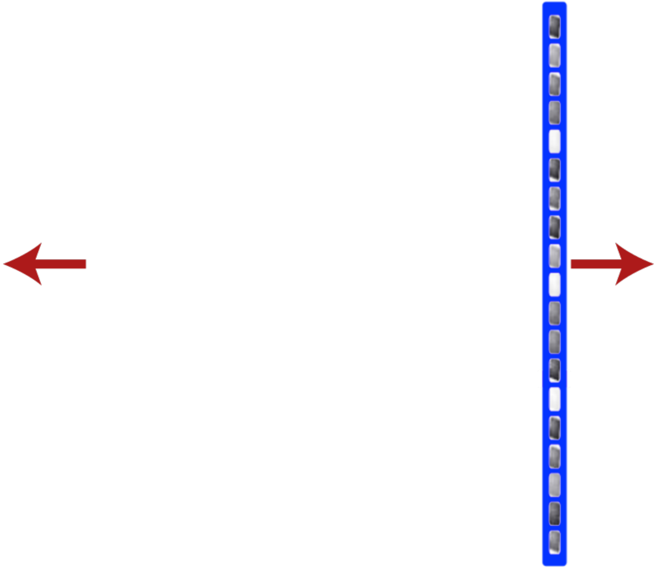
1. Gaze-contingent Focus

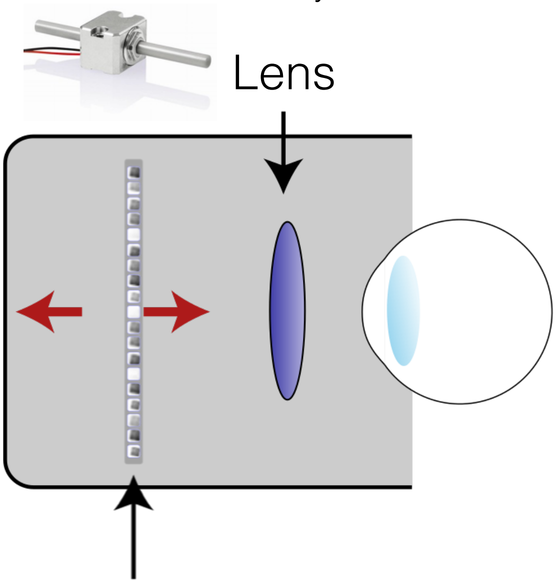
Fixed Focus



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

Adaptive Focus





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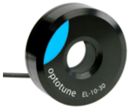
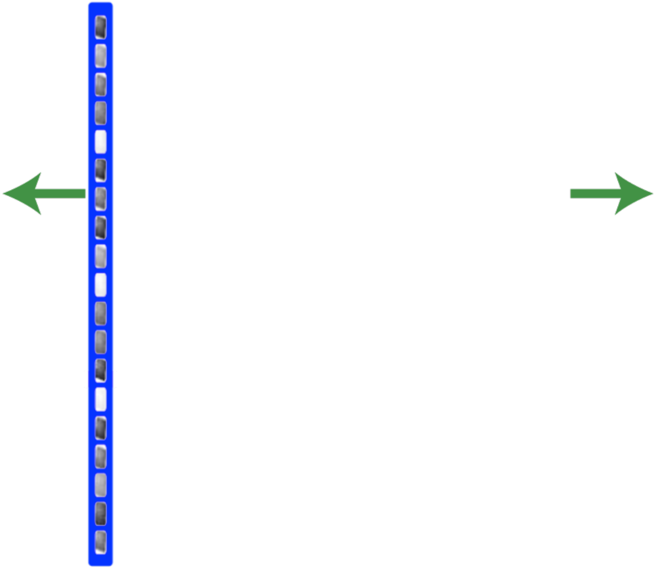
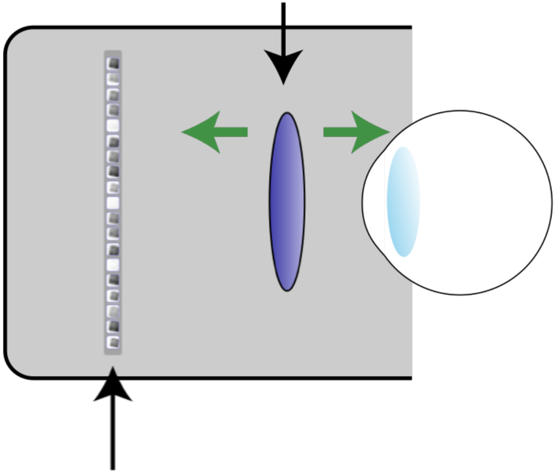
Adaptive Focus



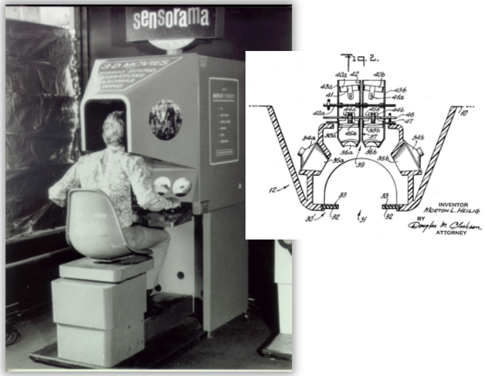
focus-tunable lens → vary f





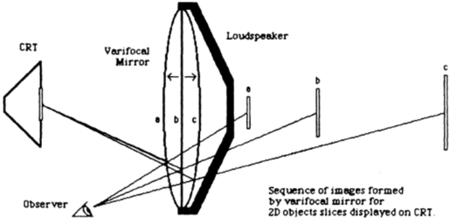
$$\frac{1}{d}+\frac{1}{d'}=\frac{1}{\boxed{f}}$$

Adaptive Focus - History



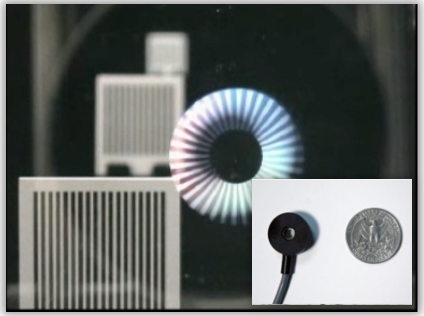
manual focus adjustment

Heilig 1962



automatic focus adjustment

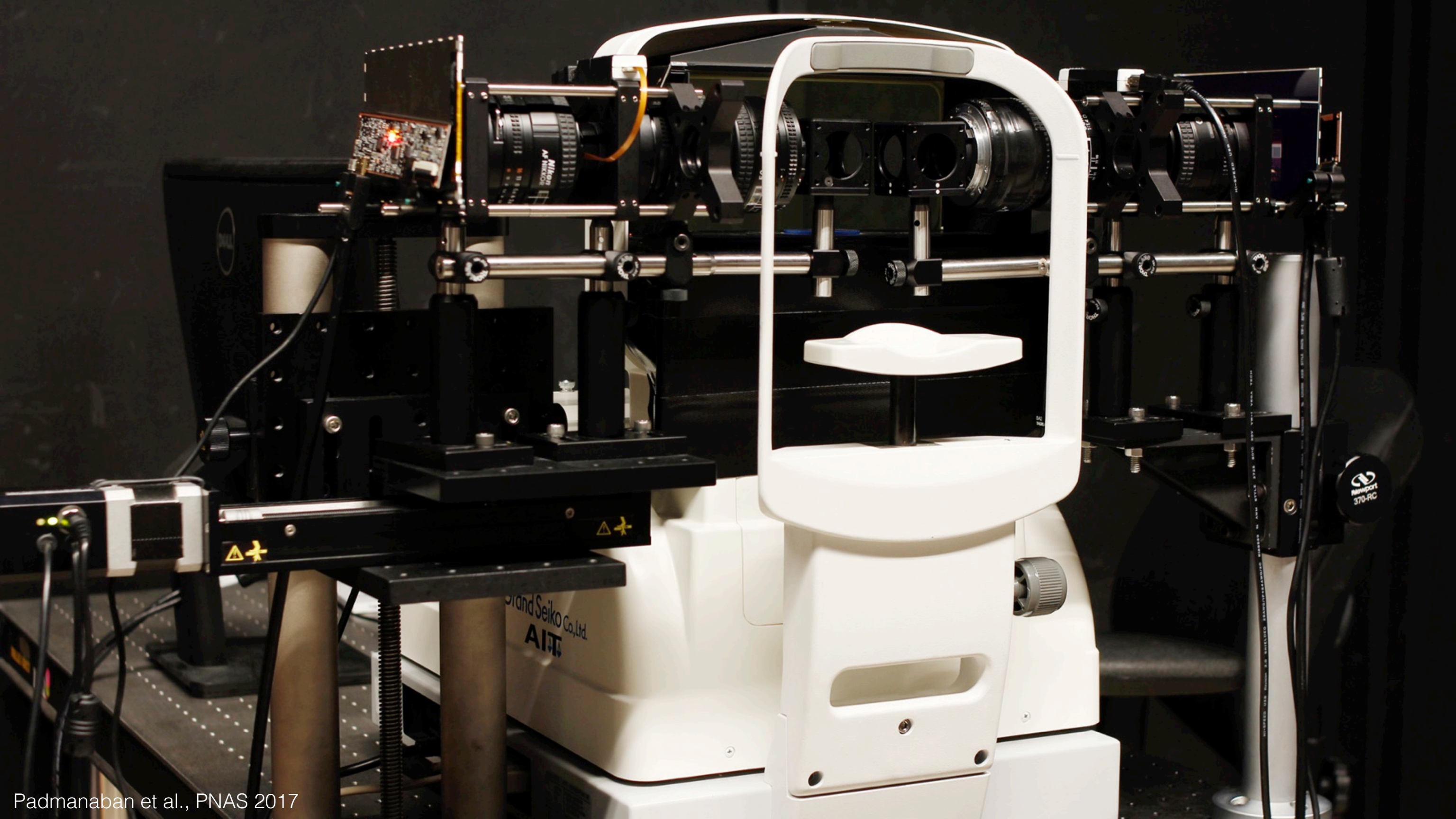
Mills 1984



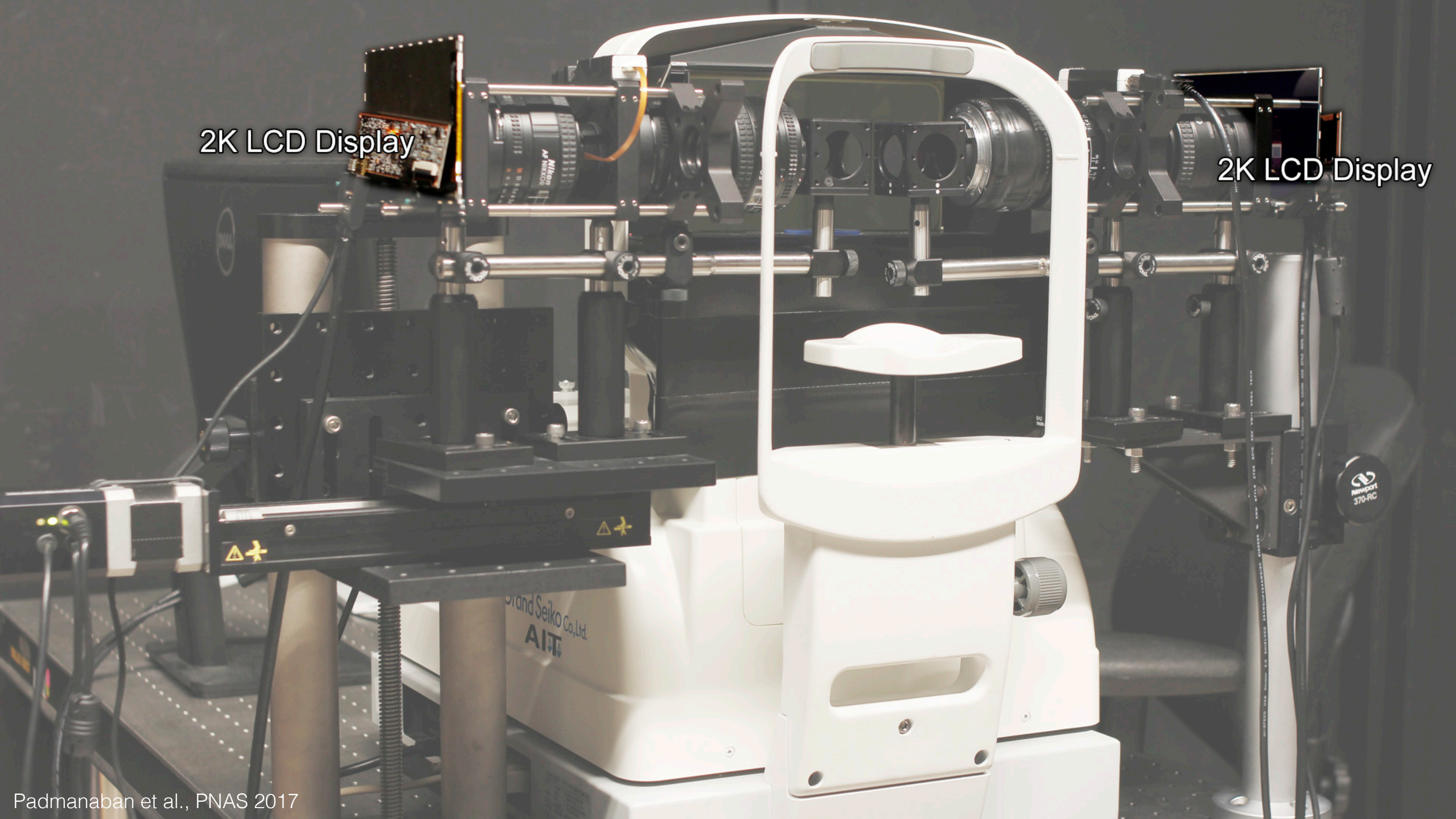
deformabe mirrors & lenses

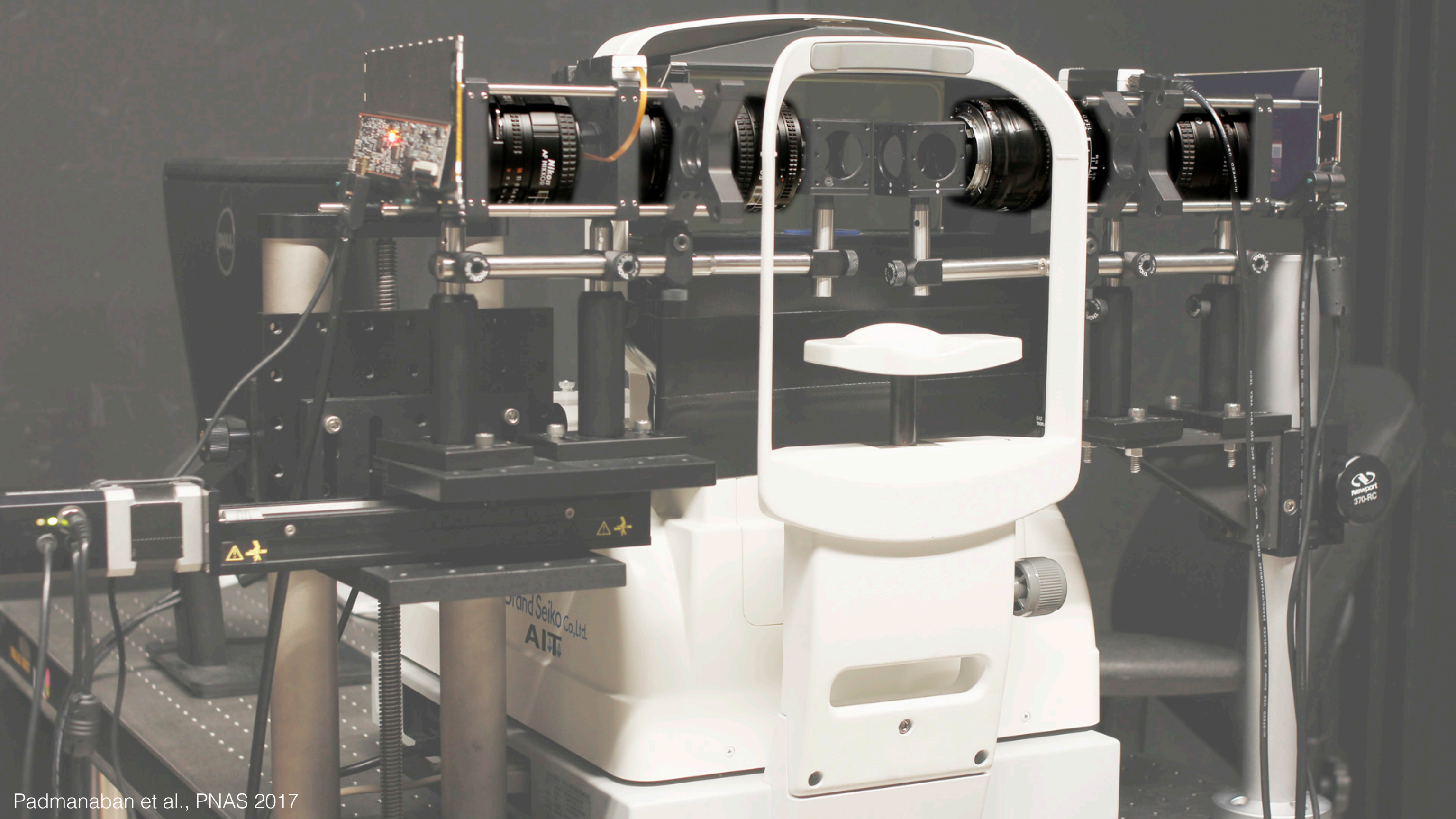
McQuaide 2003, Liu 2008

- 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

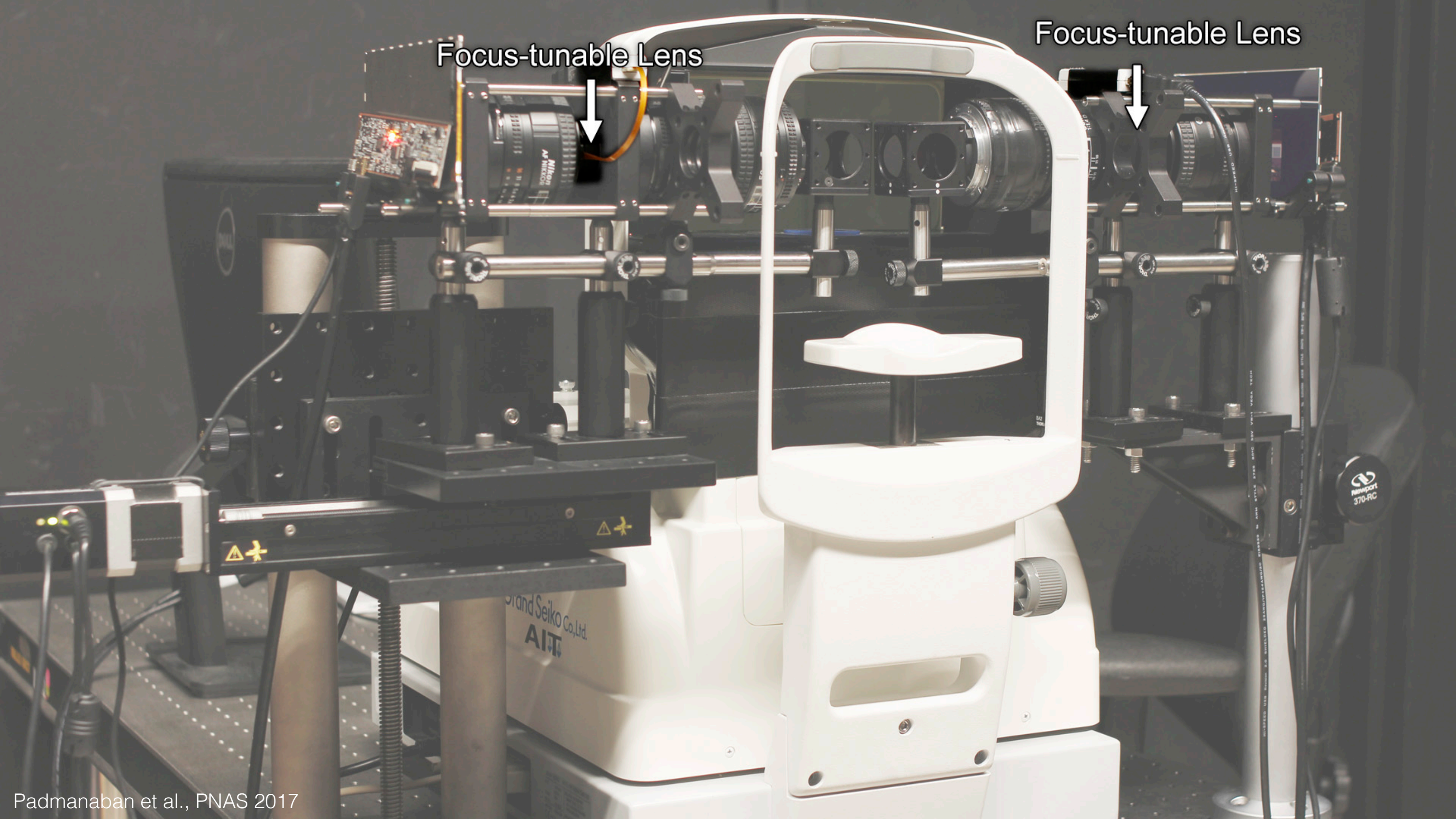


Padmanaban et al., PNAS 2017

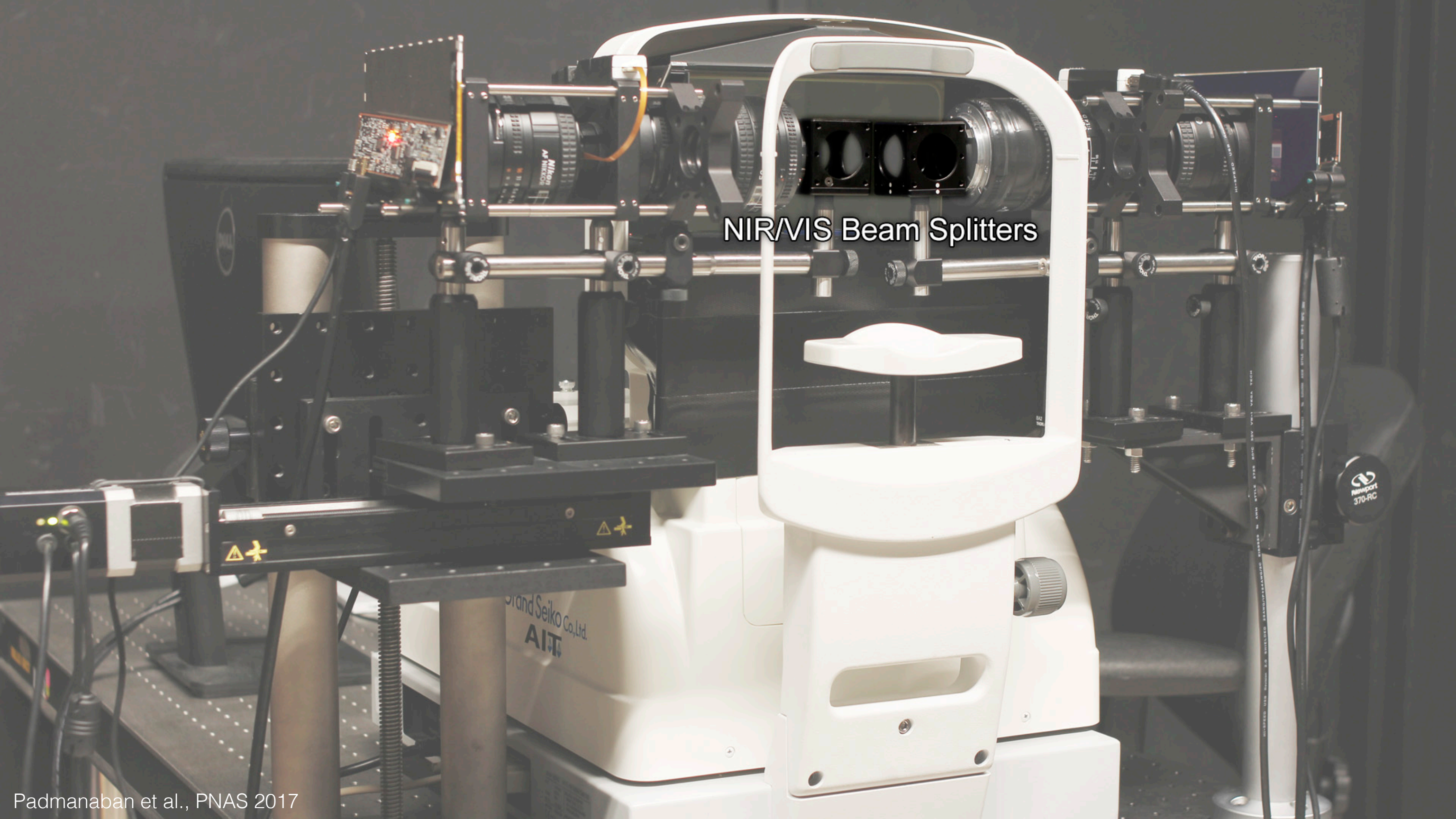

2K LCD Display
2K LCD Display
Padmanaban et al., PNAS 2017



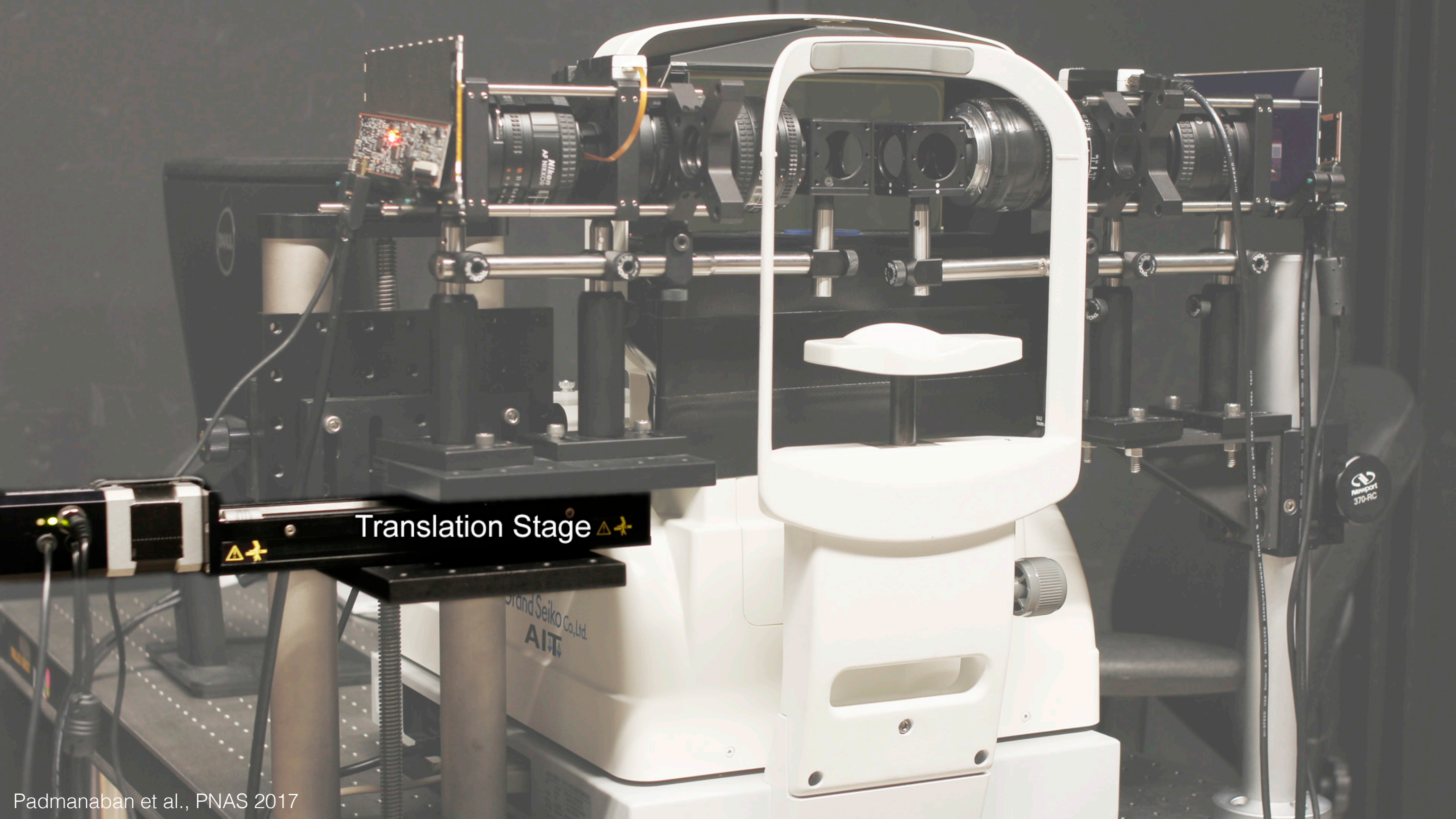
Padmanaban et al., PNAS 2017



Padmanaban et al., PNAS 2017



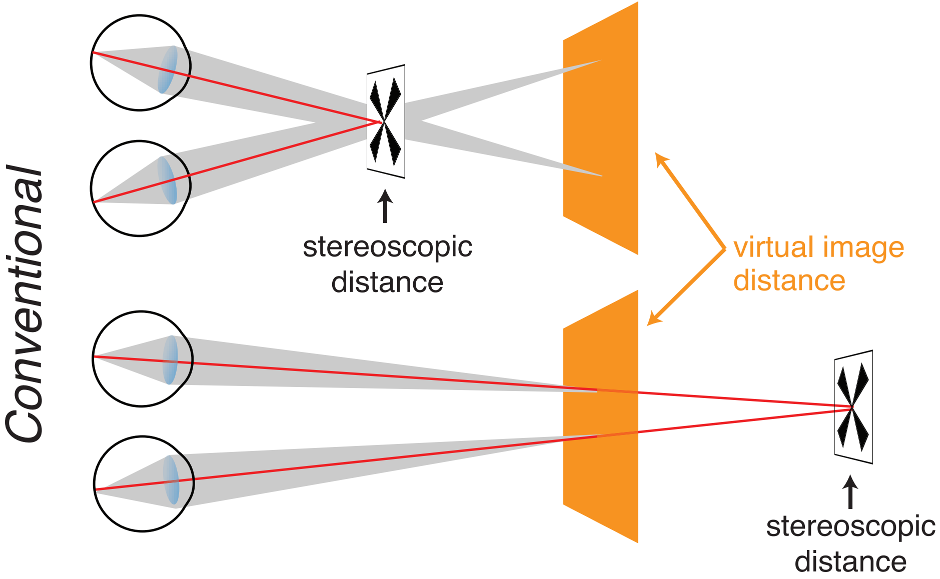
Padmanaban et al., PNAS 2017



Padmanaban et al., PNAS 2017

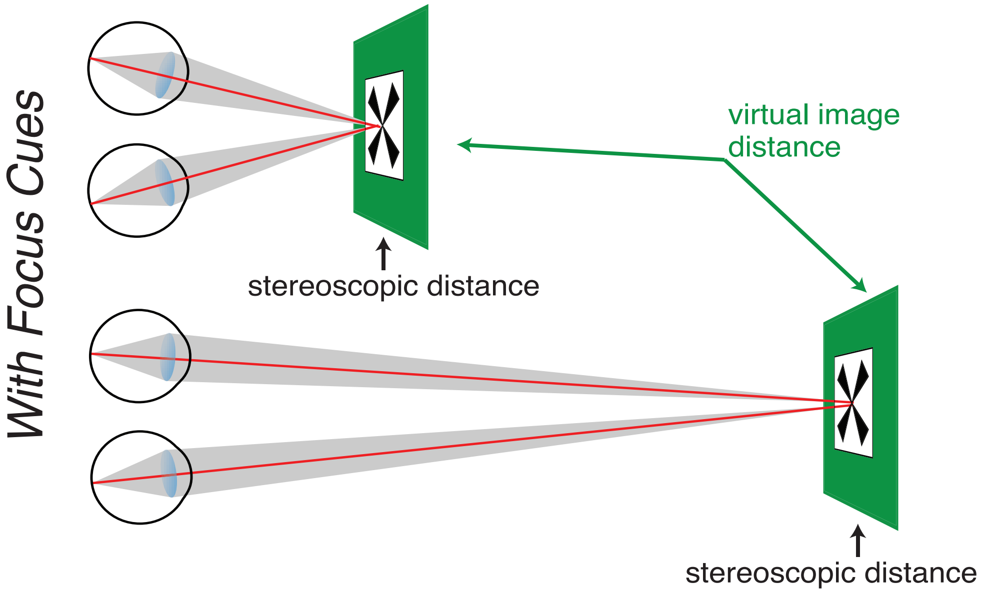

Autorefractor
Padmanaban et al., PNAS 2017

Conventional Stereo / VR Display



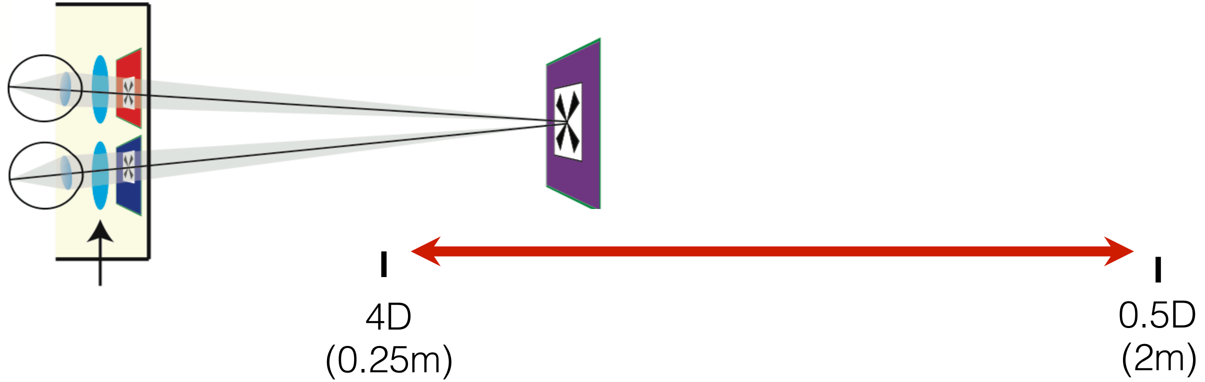
vergence
accommodation

Removing VAC with Adaptive Focus



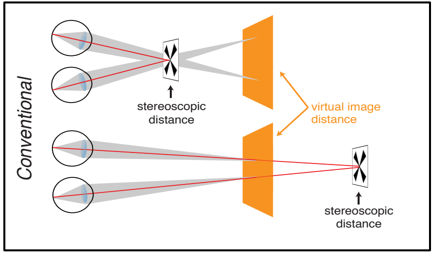
vergence
accommodation

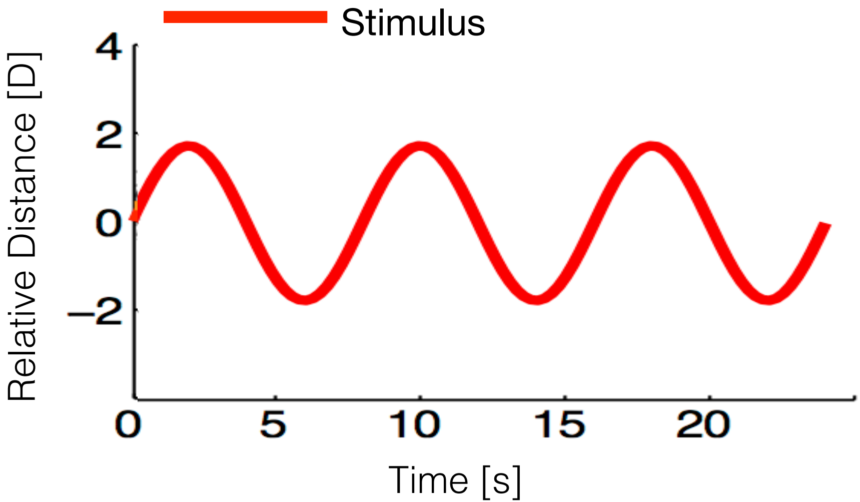
Task



Follow the target with your eyes

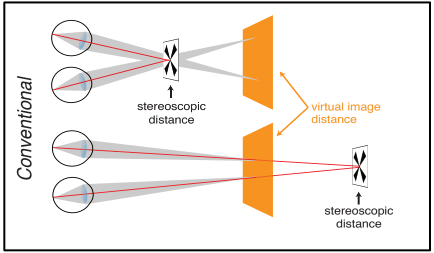
Accommodative Response

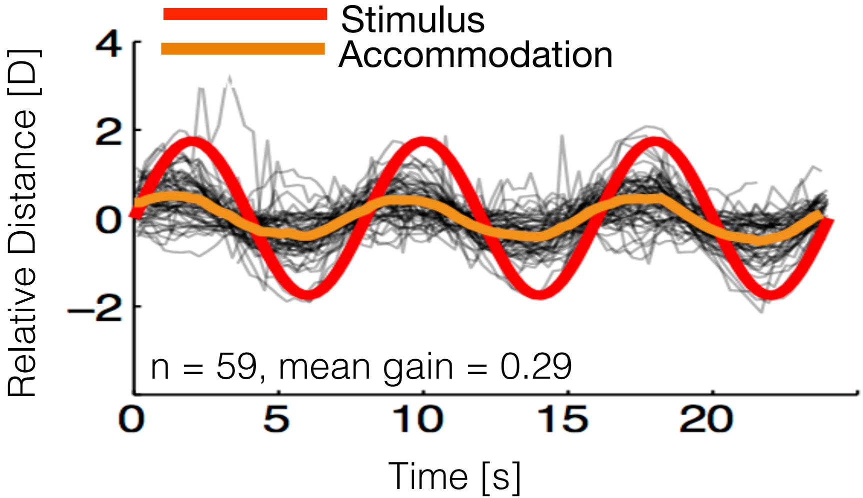




Padmanaban et al., PNAS 2017

Accommodative Response





Padmanaban et al., PNAS 2017

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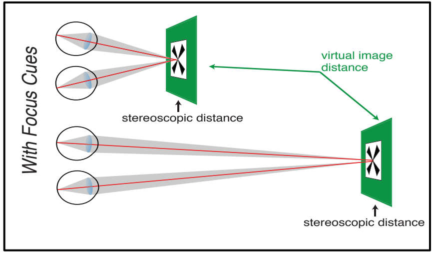

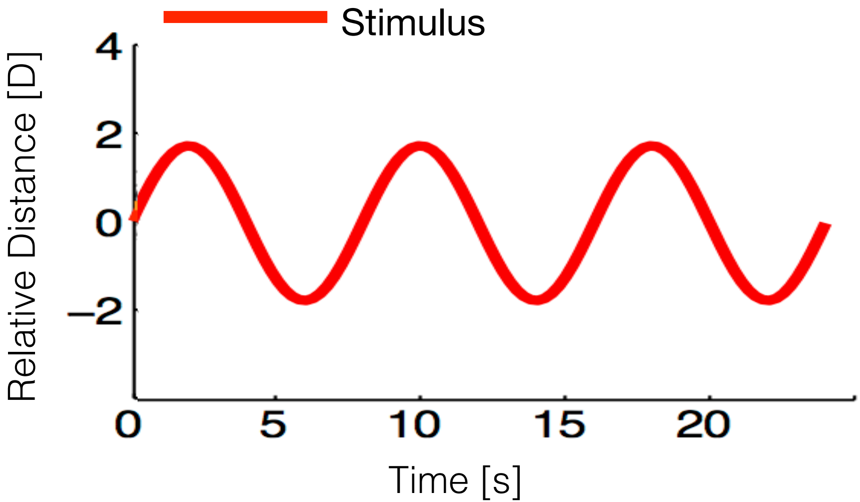

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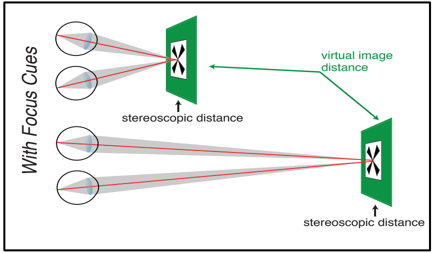
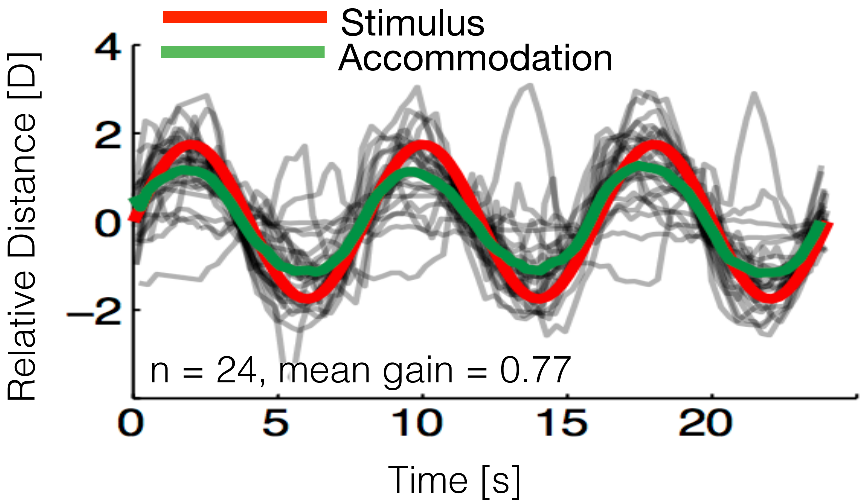
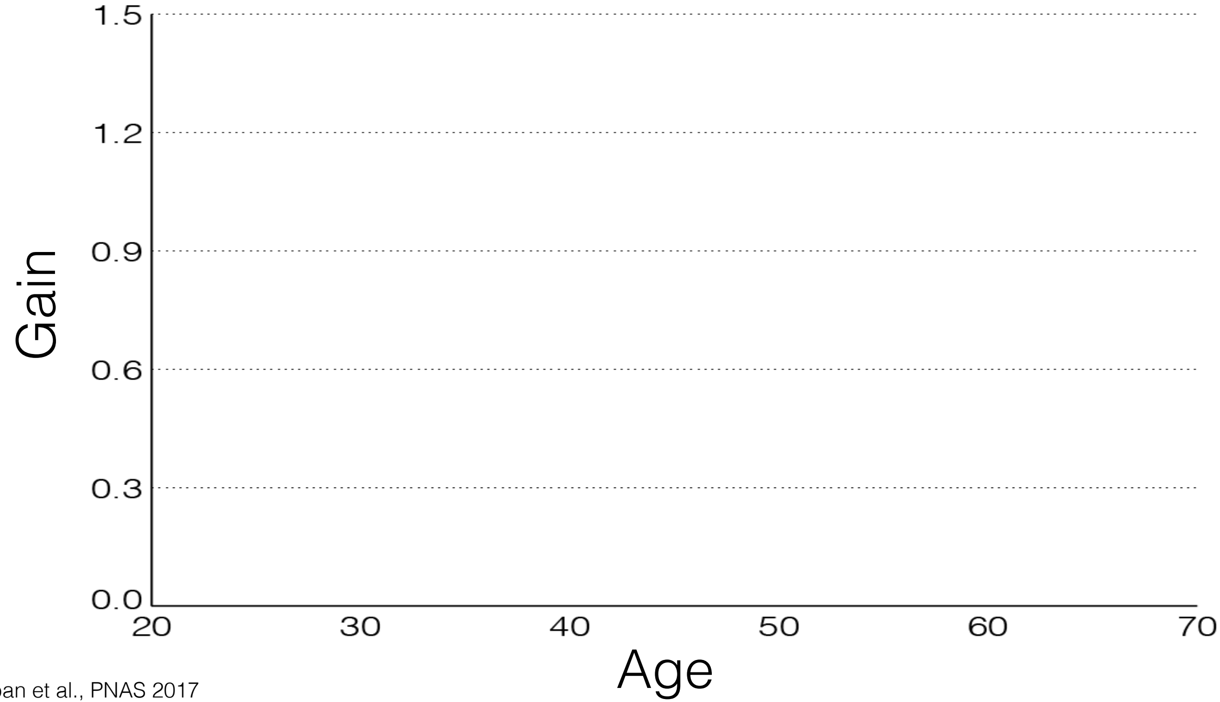




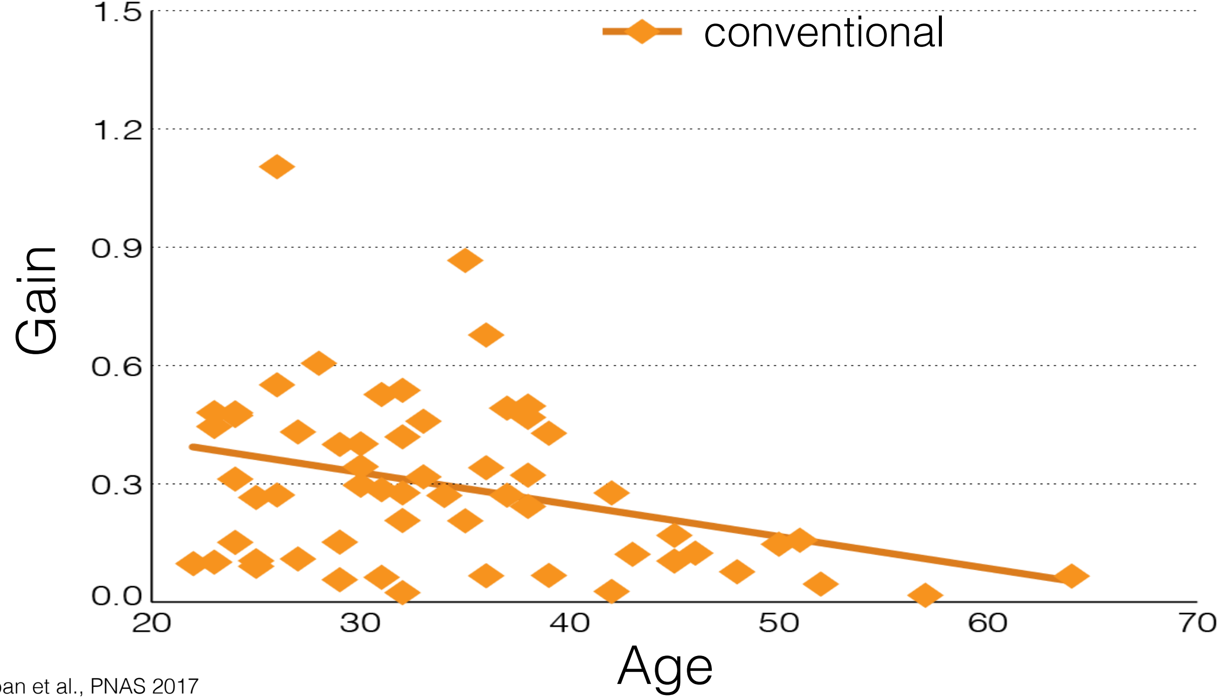
Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?



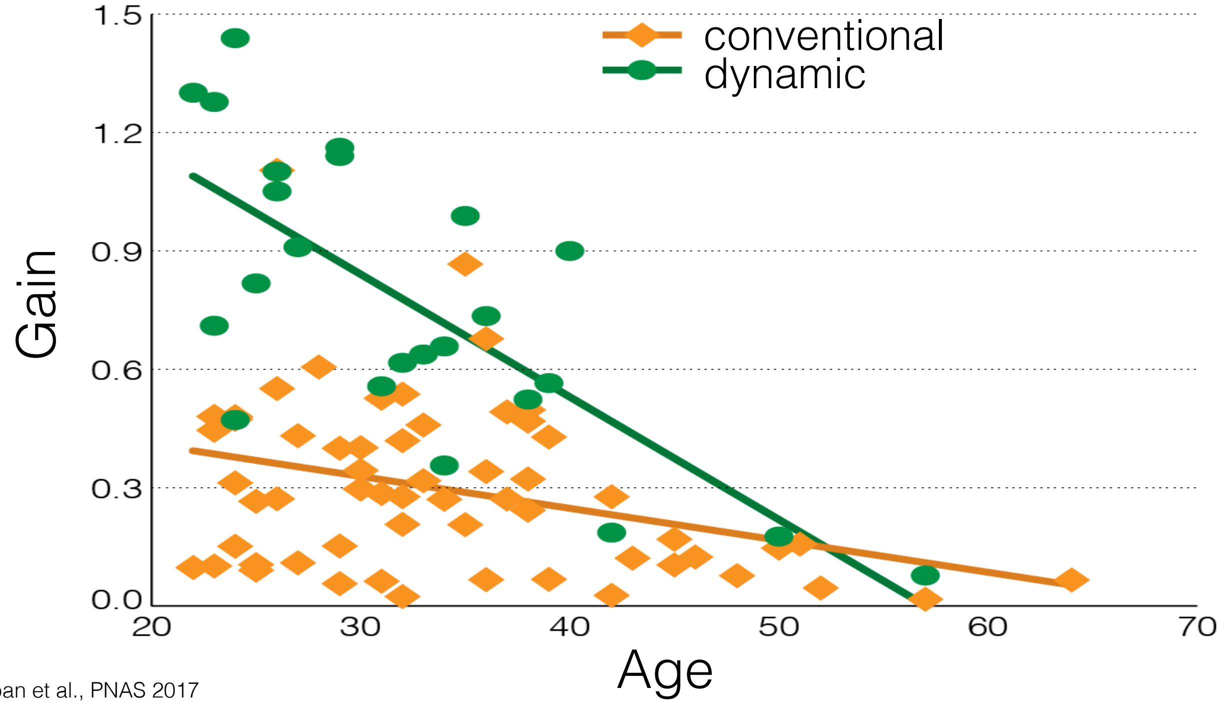
Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?



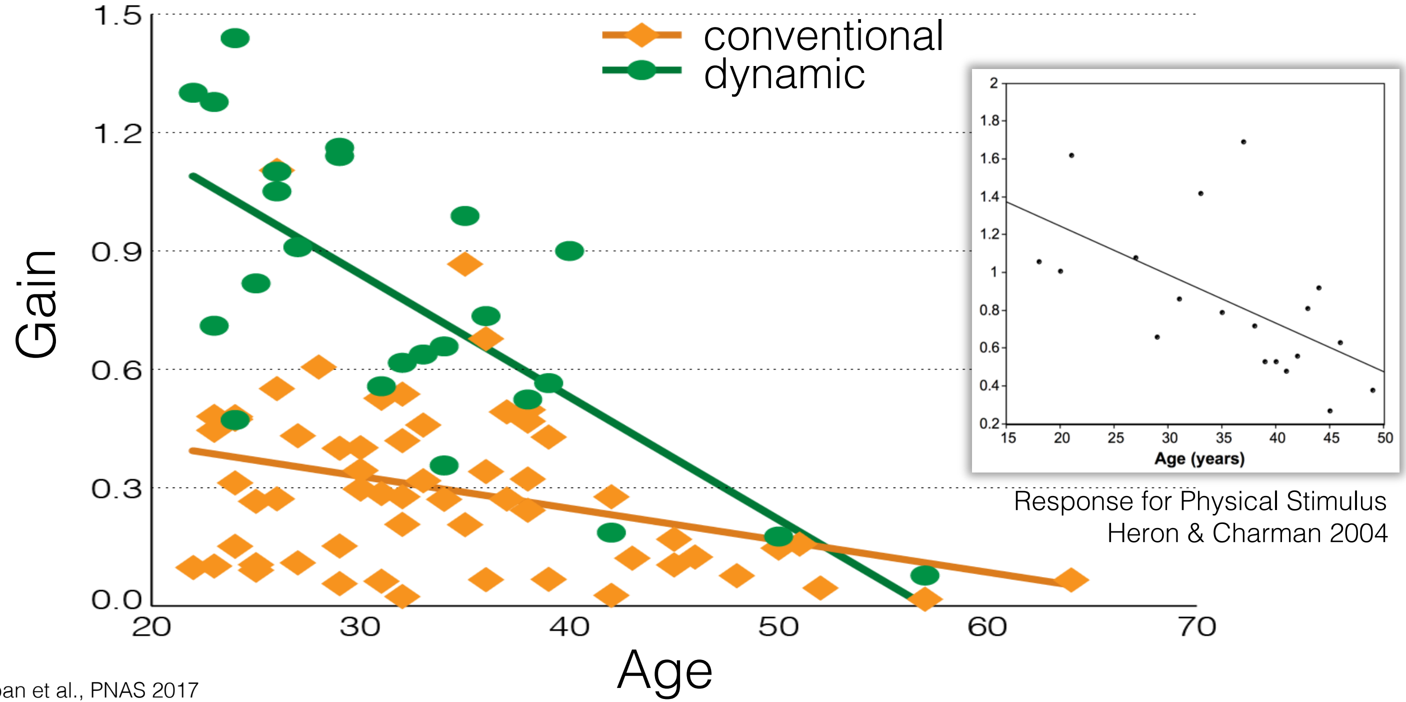
Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?



Padmanaban et al., PNAS 2017

Do Presbyopes Benefit from Dynamic Focus?

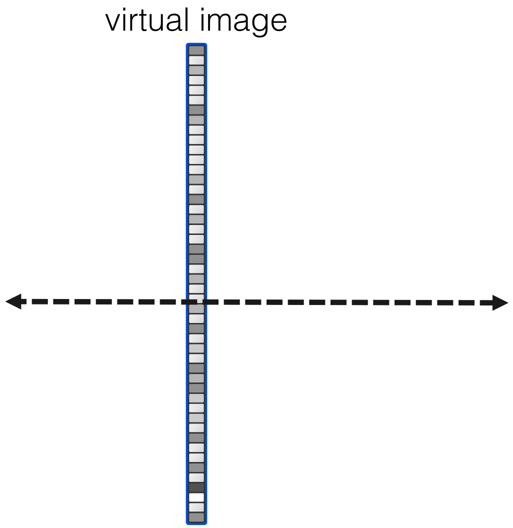


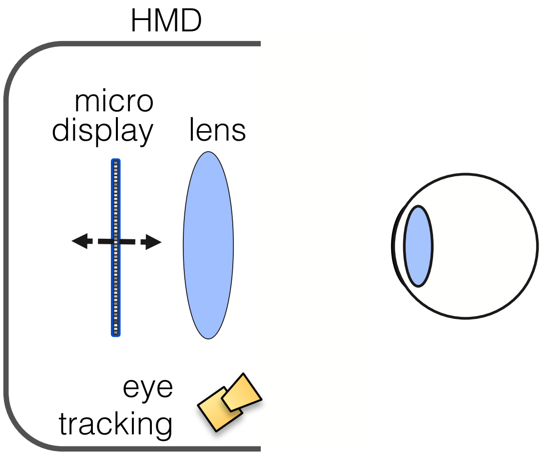
Response for Physical Stimulus
Heron & Charman 2004

Padmanaban et al., PNAS 2017

Gaze-contingent Focus

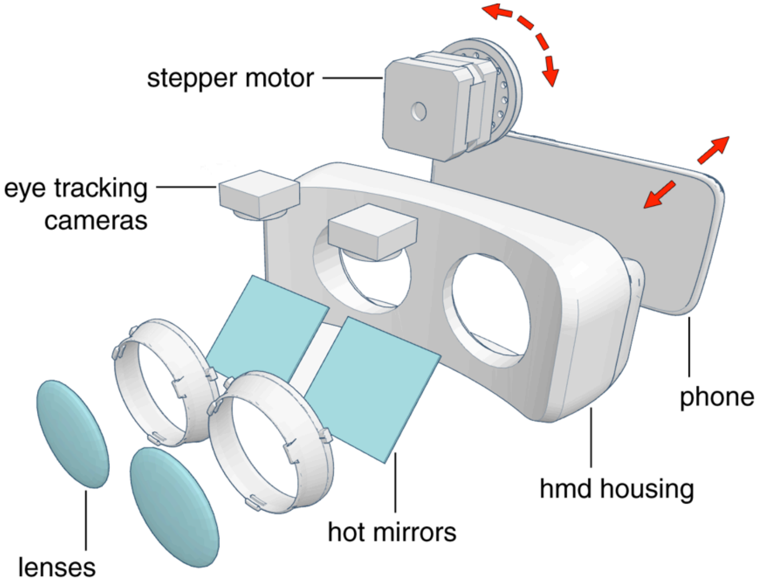
- <u>non-presbyopes</u>: adaptive focus is <u>like real world</u>, but needs eye tracking!





Padmanaban et al., PNAS 2017

Gaze-contingent Focus



Padmanaban et al., PNAS 2017

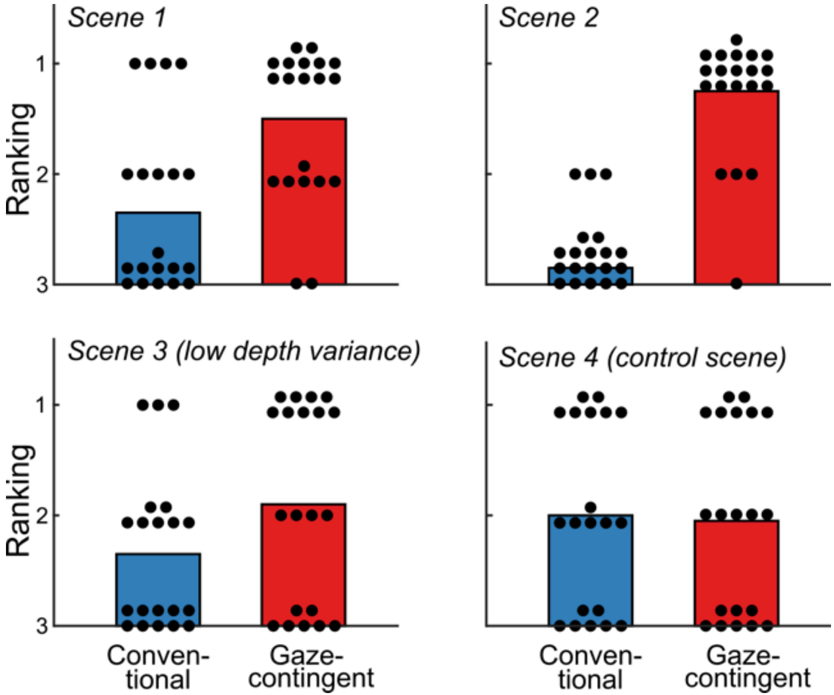
Gaze-contingent Focus

Padmanaban et al., PNAS 2017

Gaze-contingent Focus

Padmanaban et al., PNAS 2017

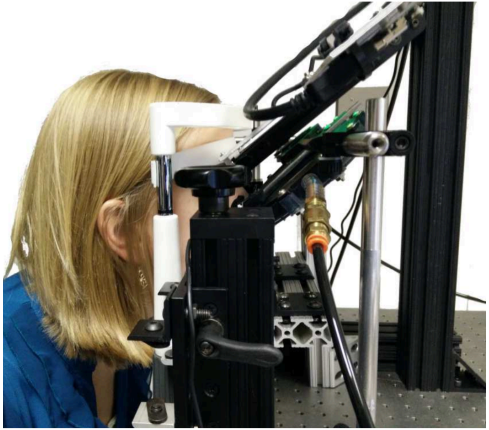
Gaze-contingent Focus – User Preference



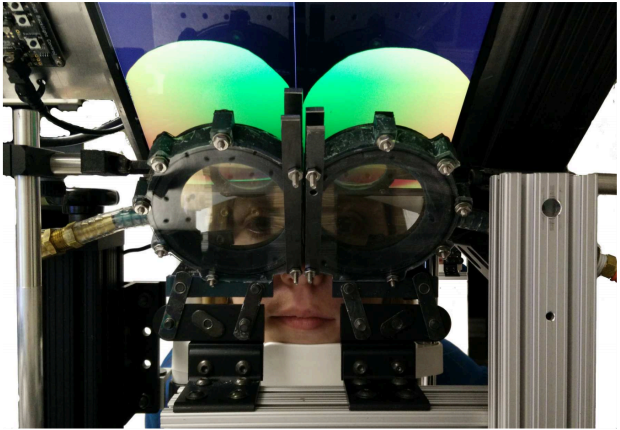
Padmanaban et al., PNAS 2017

at ACM SIGGRAPH 2016

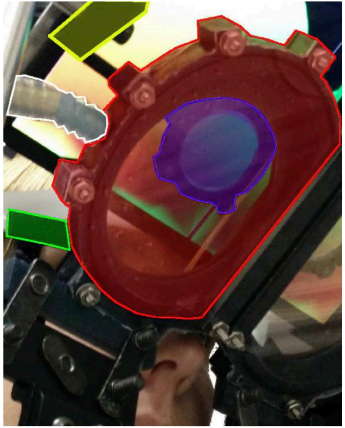
Gaze-contingent Focus for AR



Side view



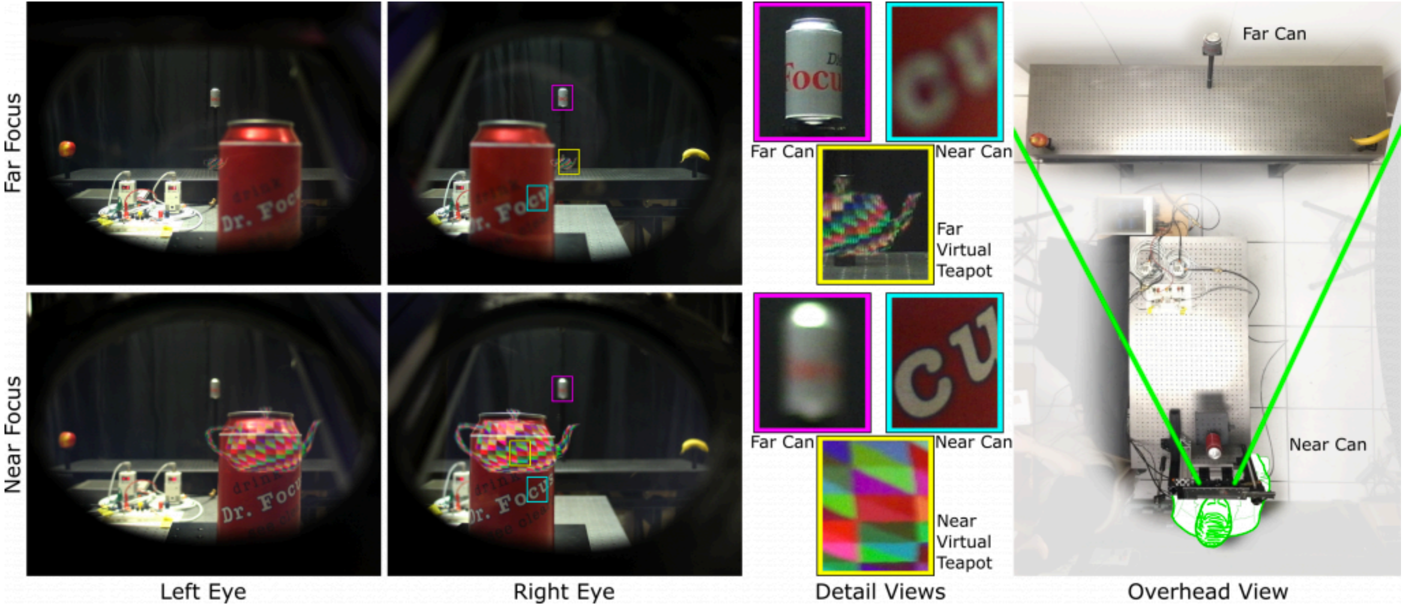
Front view



Bottom view

Dunn et al., IEEE VR 2017, Best Paper

Gaze-contingent Focus for AR



Dunn et al., IEEE VR 2017, Best Paper

Summary

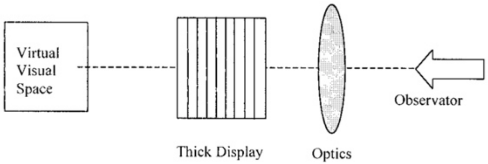
- adaptive focus drives accommodation and can correct for refractive errors (myopia, hyperopia)

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

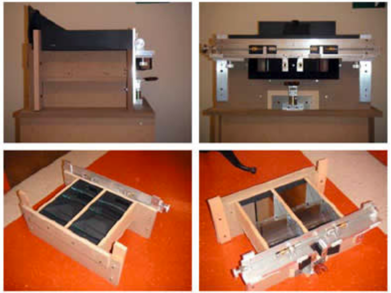
- presbyopes require fixed focal plane with correction

2. Multiplane Near-eye Displays

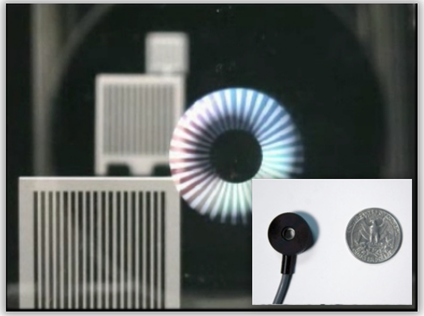
Multiplane VR Displays



idea introduced
Rolland et al. 2000



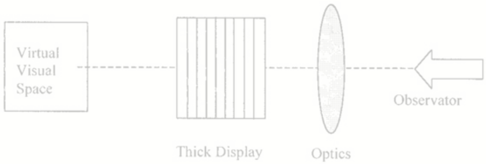
benchtop prototype
Akeley 2004



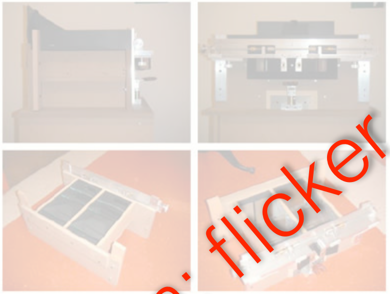
near-eye display prototype
Liu 2008, Love 2009

- 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 …

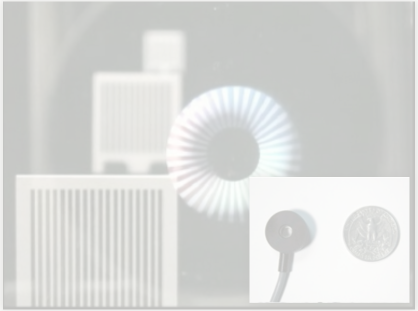
Multiplane VR Displays



idea introduced
Rolland et al. 2000



benchtop prototype
Akeley 2004



near-eye display prototype
Liu 2008, Love 2009

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
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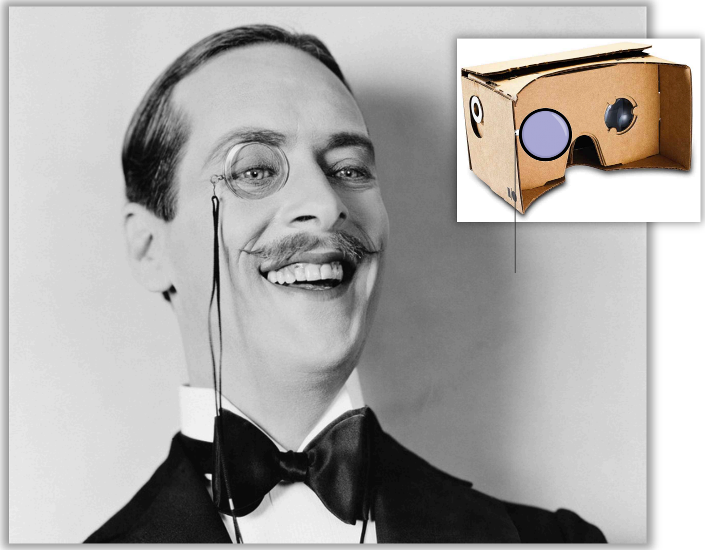
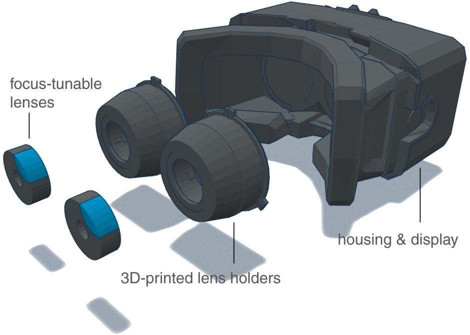
- Liu S, Cheng D, Hua H (2008) An optical see-through head mounted display with addressable focal planes in Proc. ISMAR
- Love GD et al. (2009) High-speed switchable lens enables the development of a volumetric stereoscopic display. Optics Express
- … many more ...

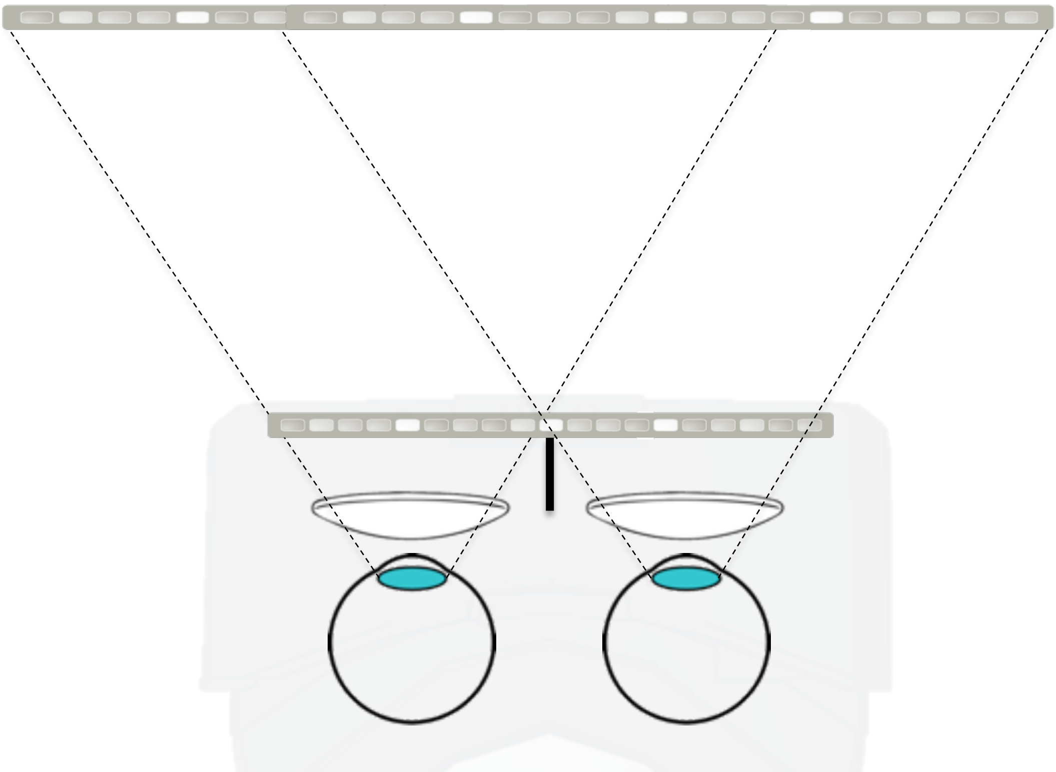
3. Monovision Near-eye Displays

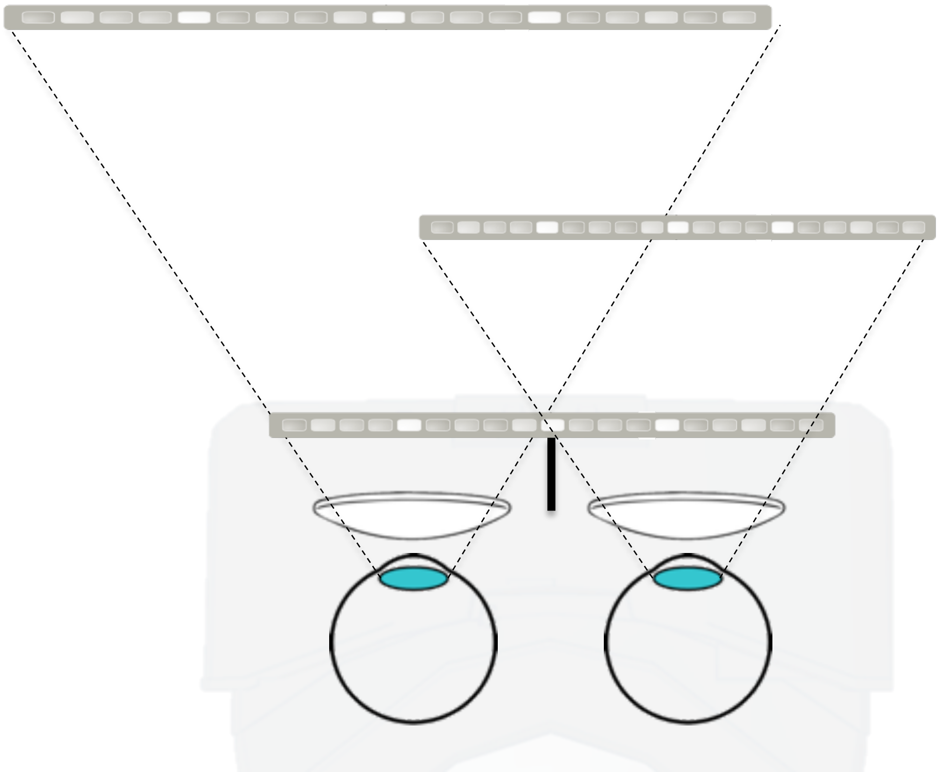
Monovision VR





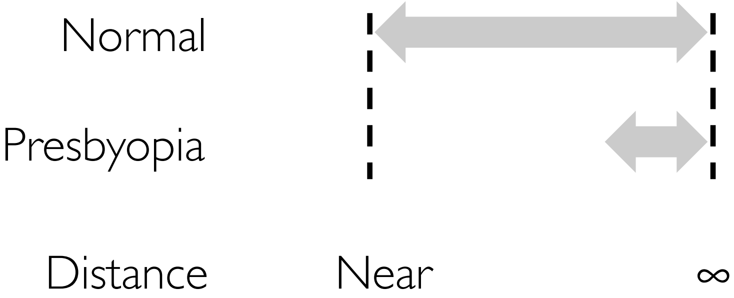
Konrad et al., SIGCHI 2016; Johnson et al., Optics Express 2016; Padmanaban et al., PNAS 2017





Can the eyes switch focus between two planes in Monovision?

Presbyopia

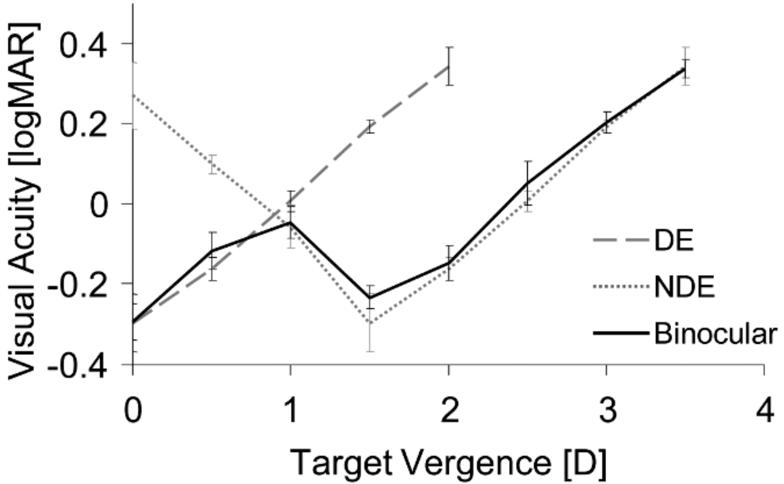


http://www.md-health.com/Monovision.html

Near Vision

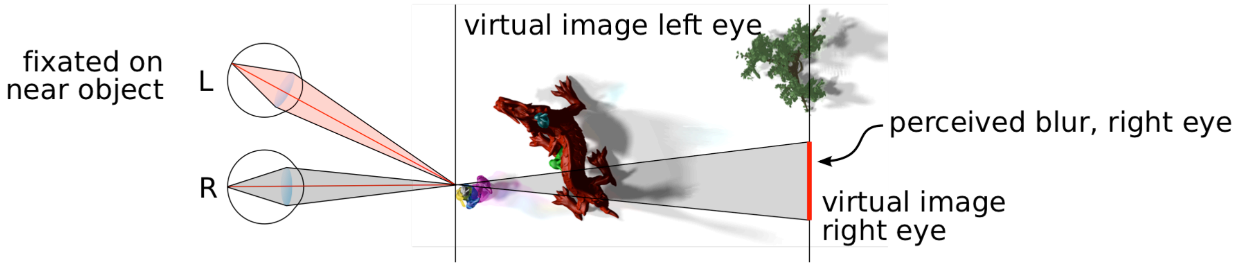
Far Vision

Monovision increases visual acuity

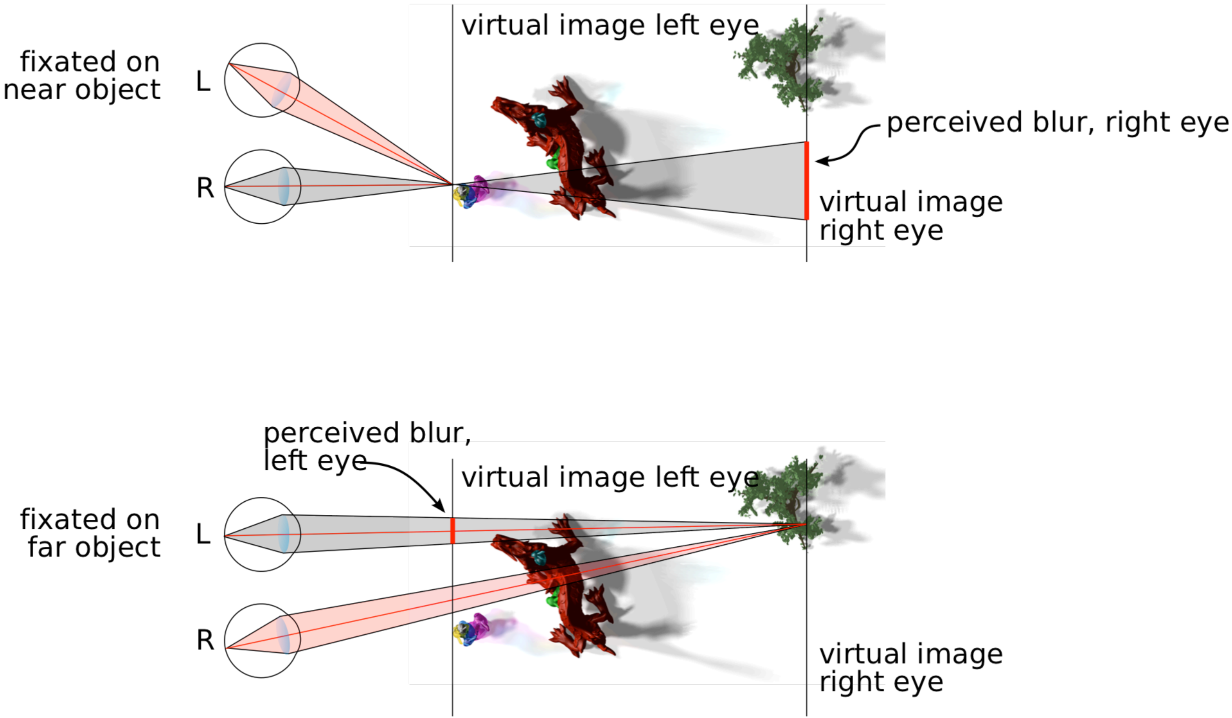


Zheleznyak *et al*. Modified Monovision With Spherical Aberration to Improve Presbyopic Through-Focus Visual Performance, 2013

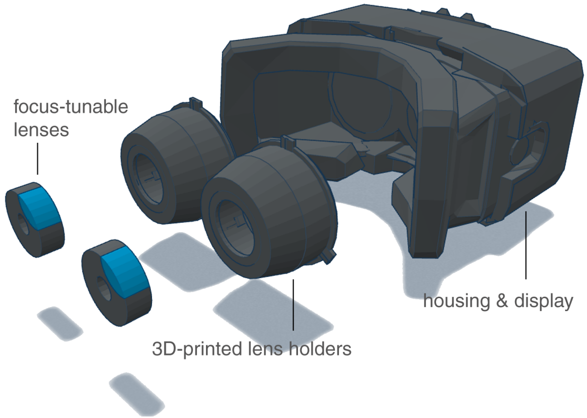
Monovision for non-presbyopic viewers in VR?

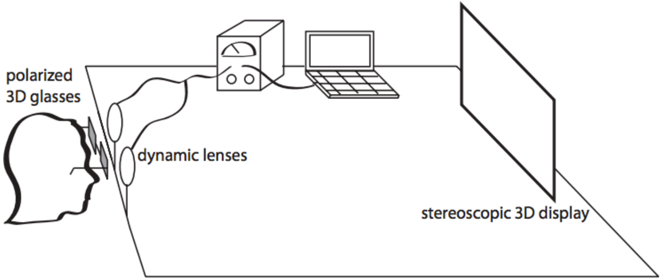


Monovision for non-presbyopic viewers in VR?



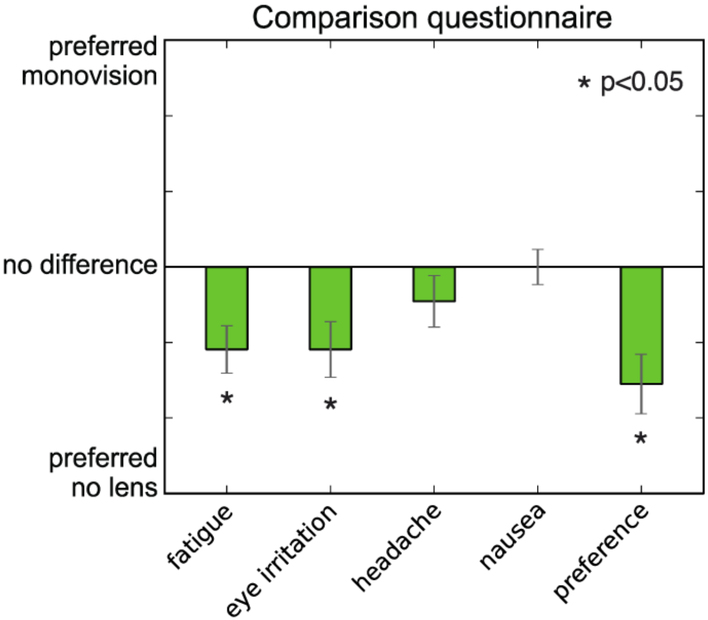
Recent Implementations



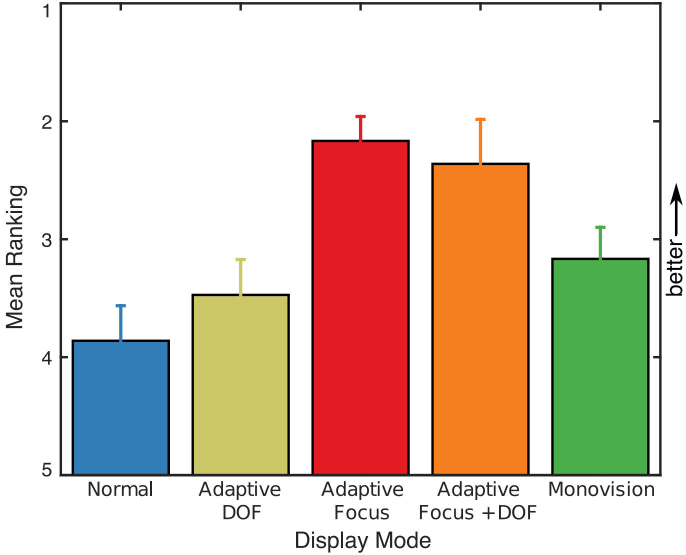


Konrad *et al*. SIGCHI, 2016
Johnson *et al*. Optics Express, 2016

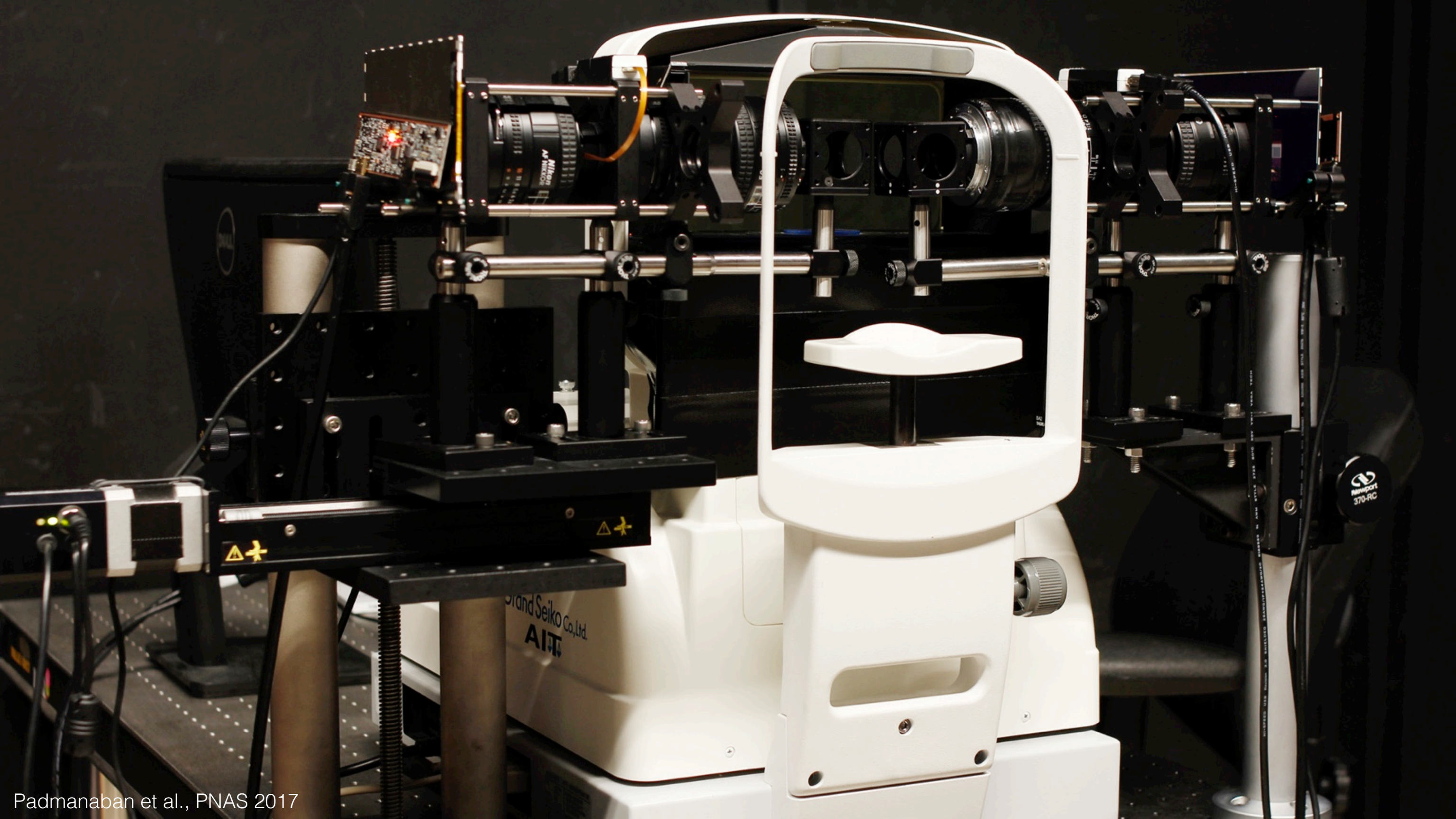
Inconclusive Results



Johnson *et al*. Optics Express, 2016

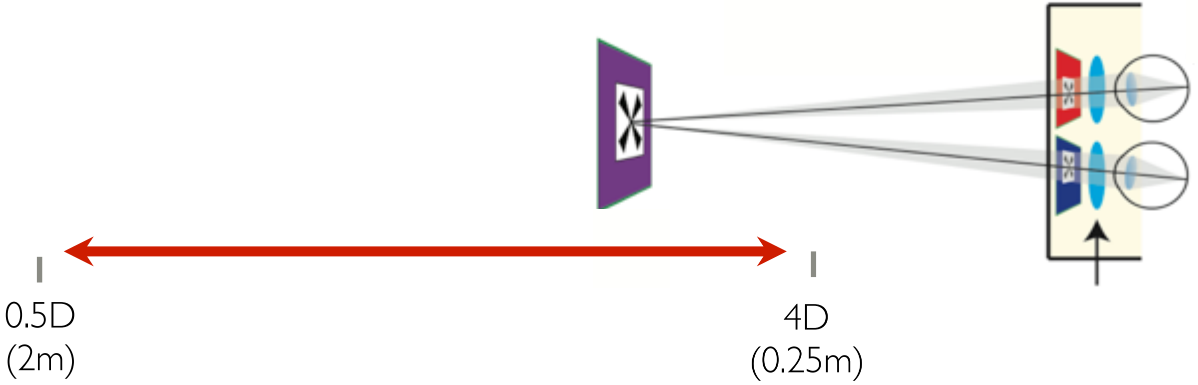


Konrad *et al*. SIGCHI, 2016



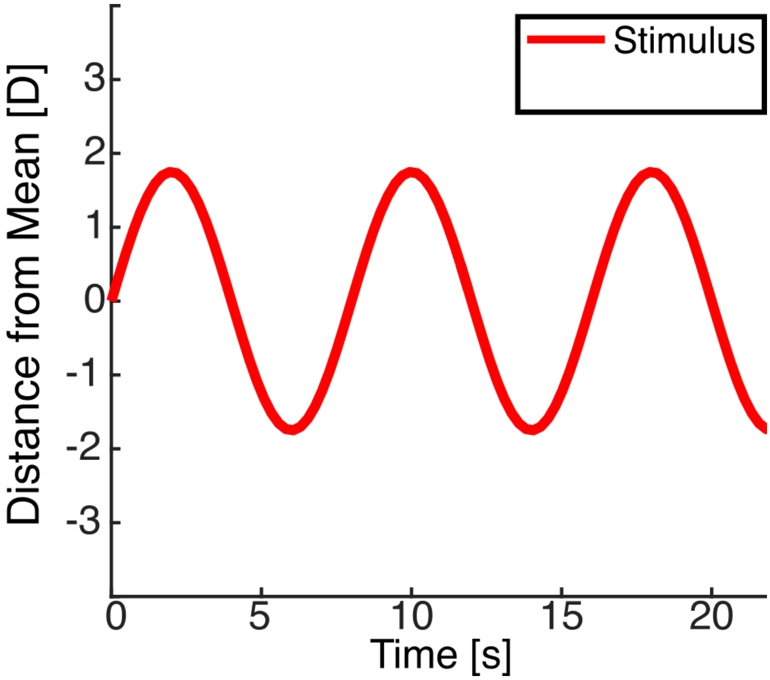
Padmanaban et al., PNAS 2017

Task #1

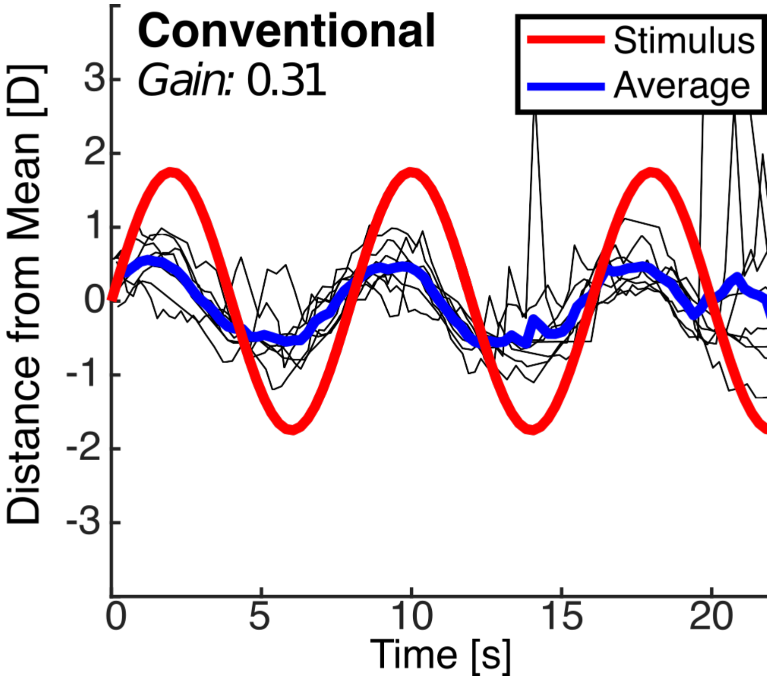


Follow the target with your eyes

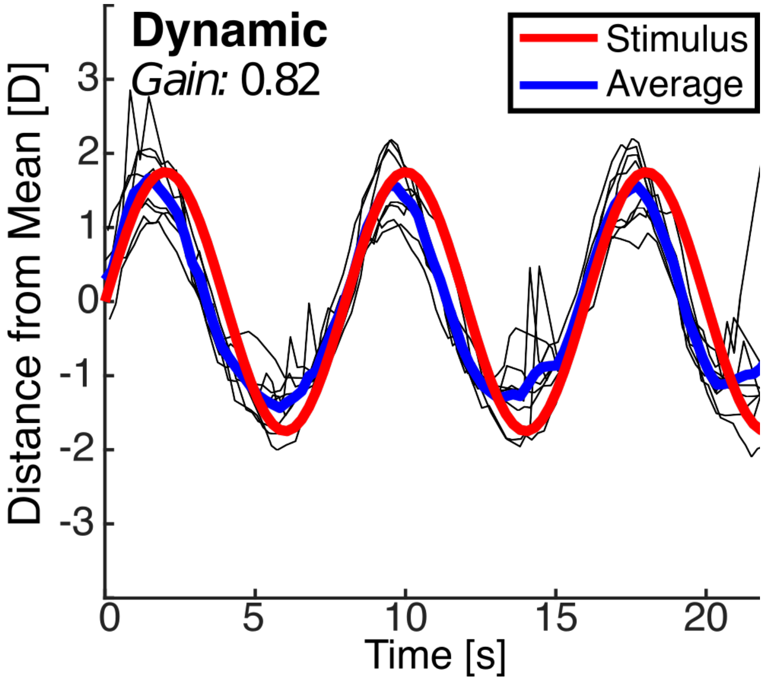
Stimulus



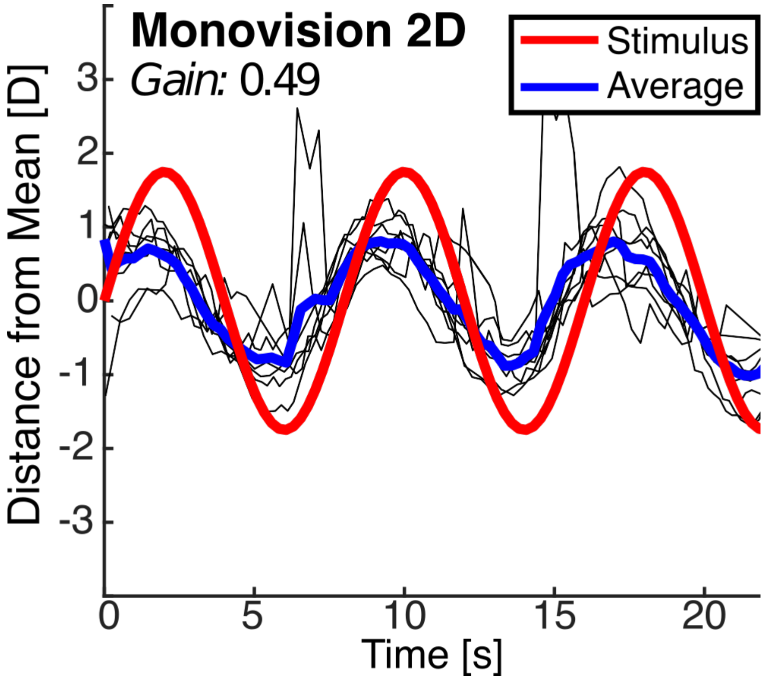
Accommodation response for conventional display



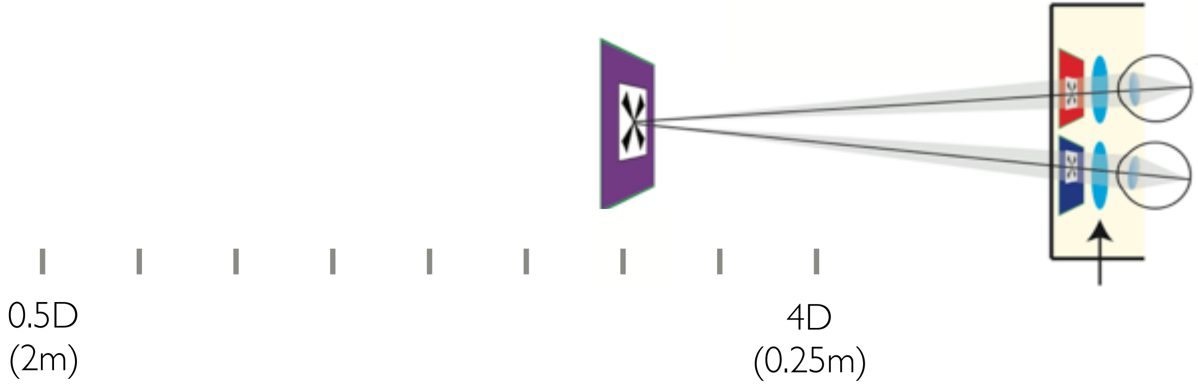
Accommodation response for dynamic display



Accommodation response for Monovision Display

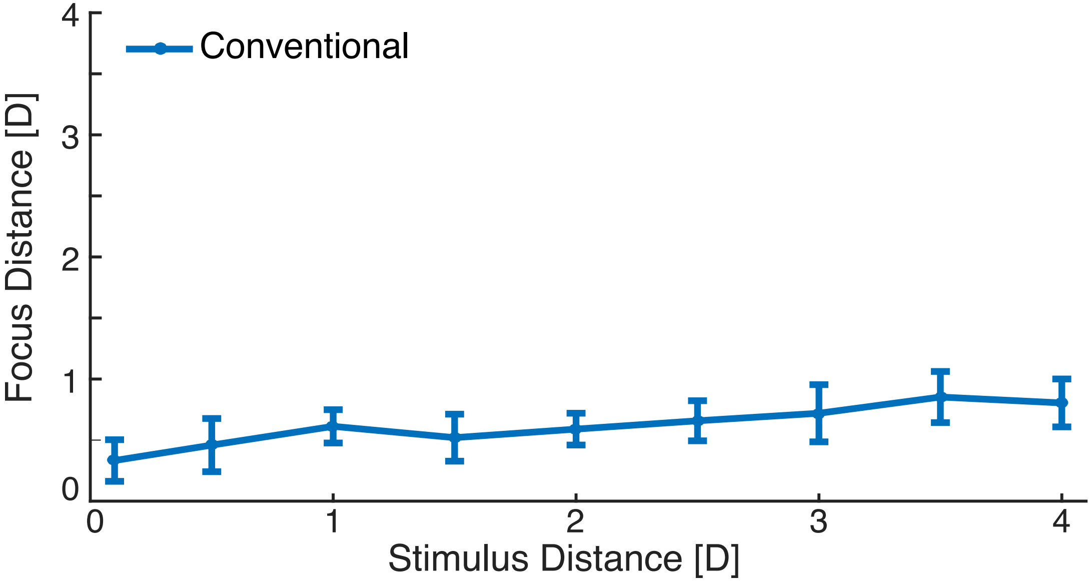


Task #2

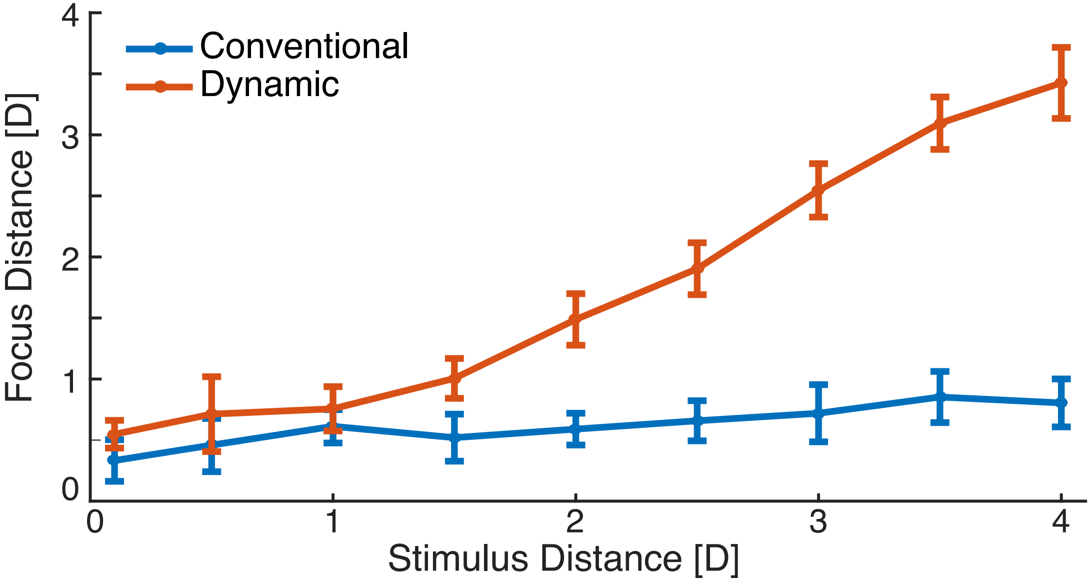


Look at each target

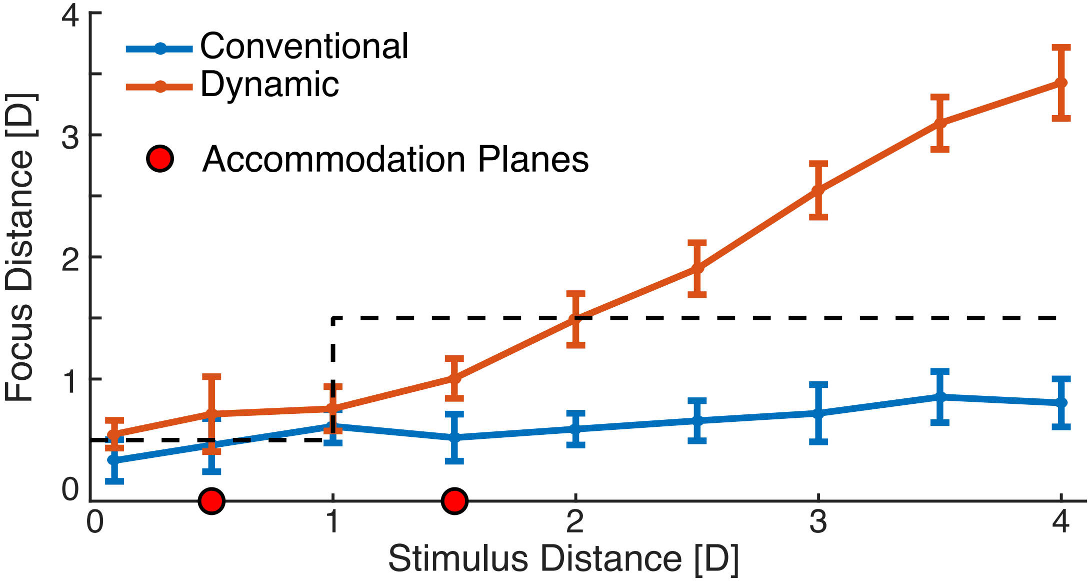
Step Response For Monovision 1D



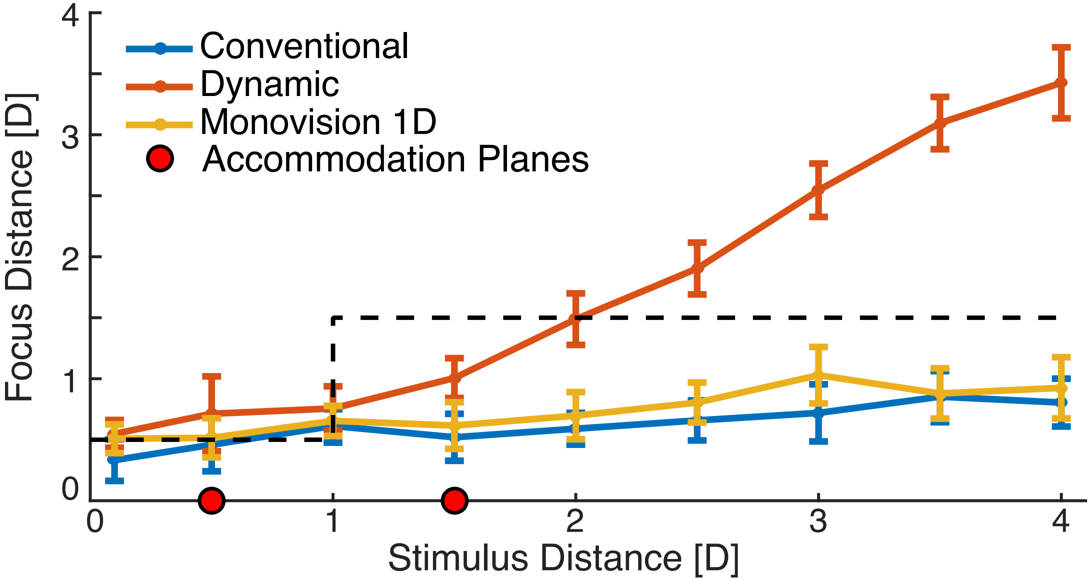
Step Response For Monovision 1D



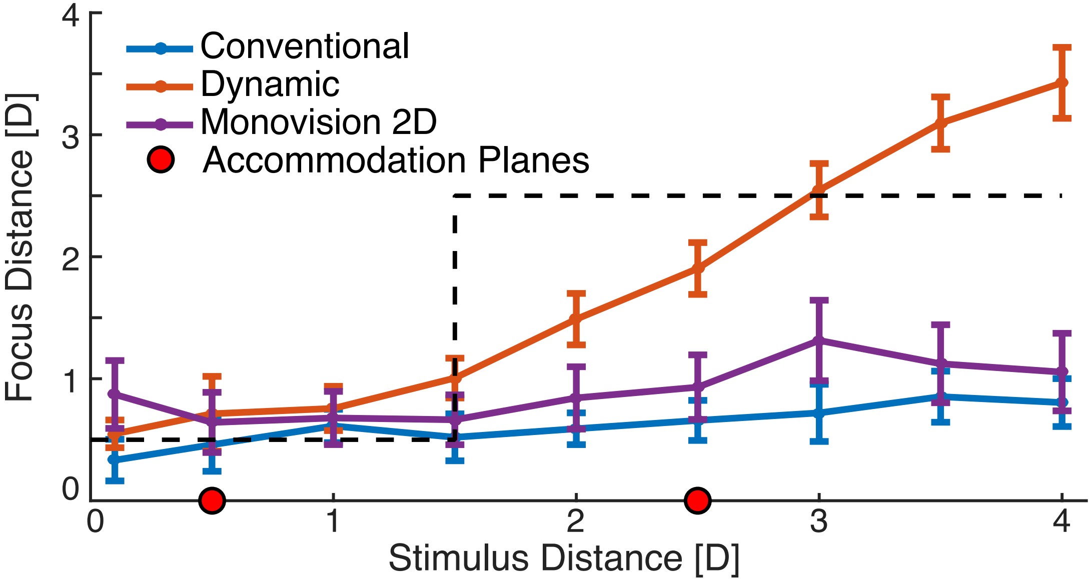
Step Response For Monovision 1D



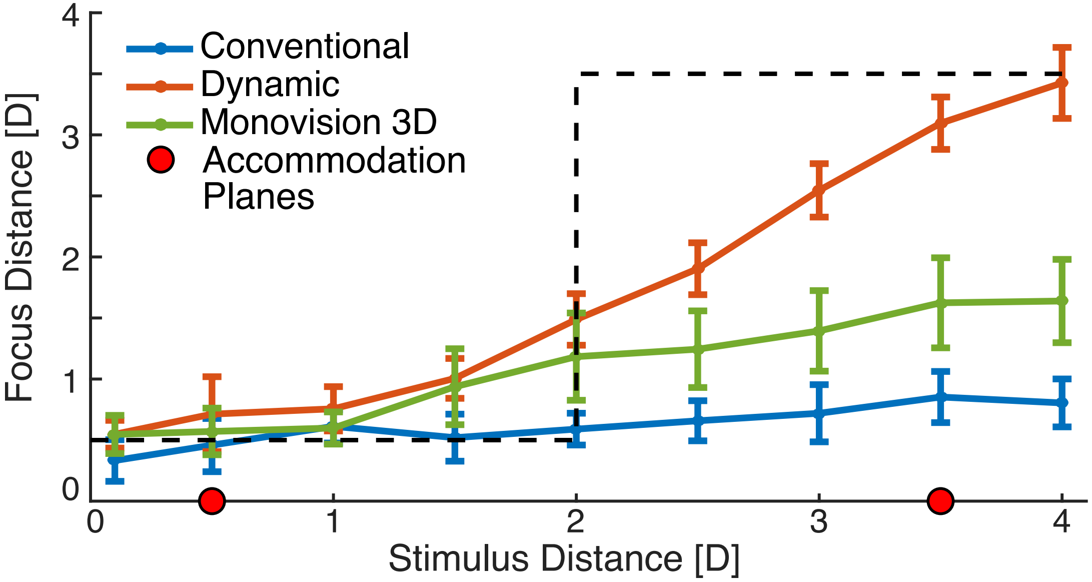
Step Response For Monovision 1D

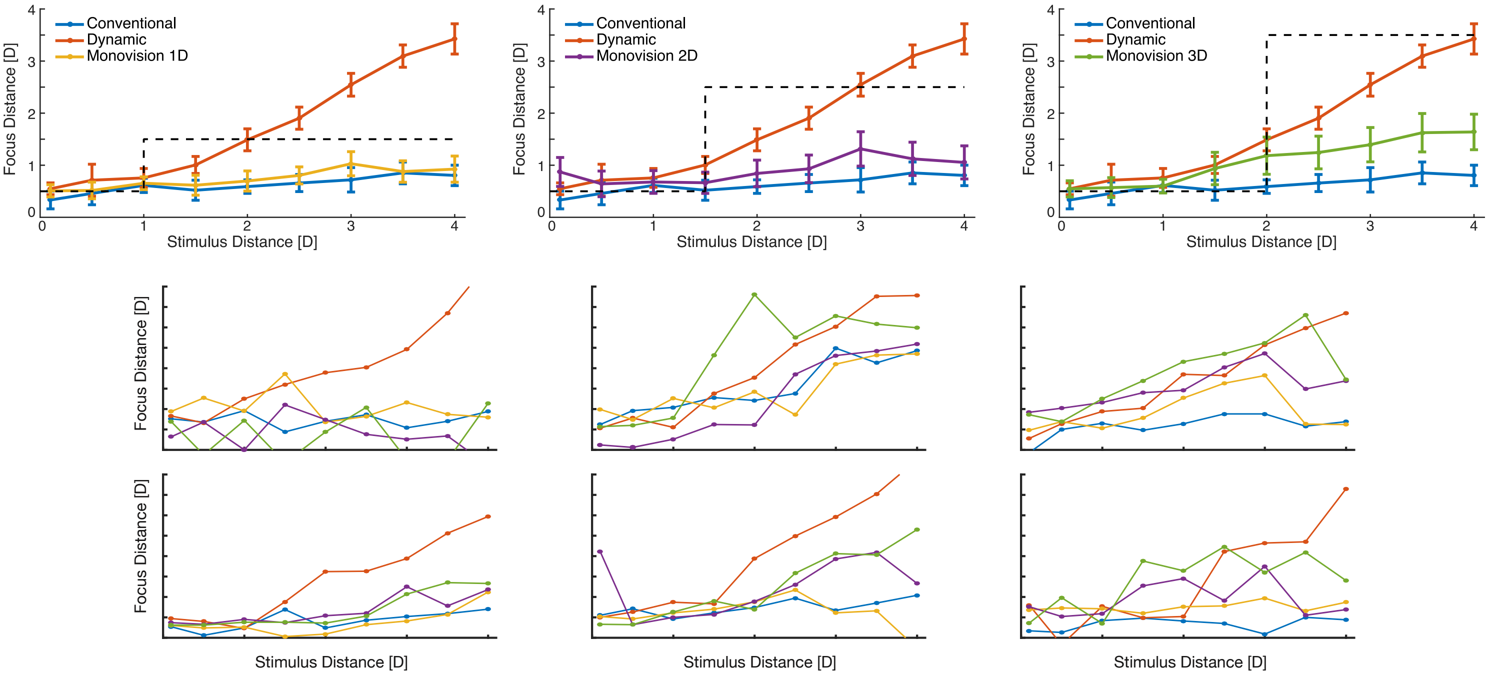


Step Response For Monovision 2D



Step Response For Monovision 3D

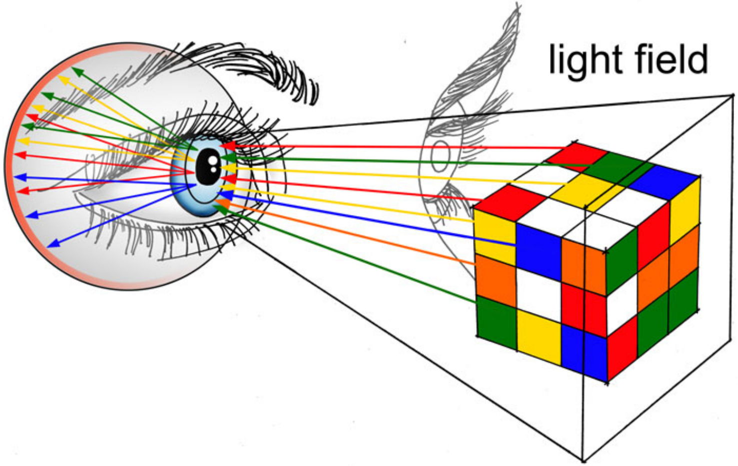




Conventional
Dynamic
Monovision 1D
Monovision 2D
Monovision 3D
Focus Distance [D]
Stimulus Distance [D]
0
1
2
3
4

4. Light Field Displays

Near-eye Light Field Displays

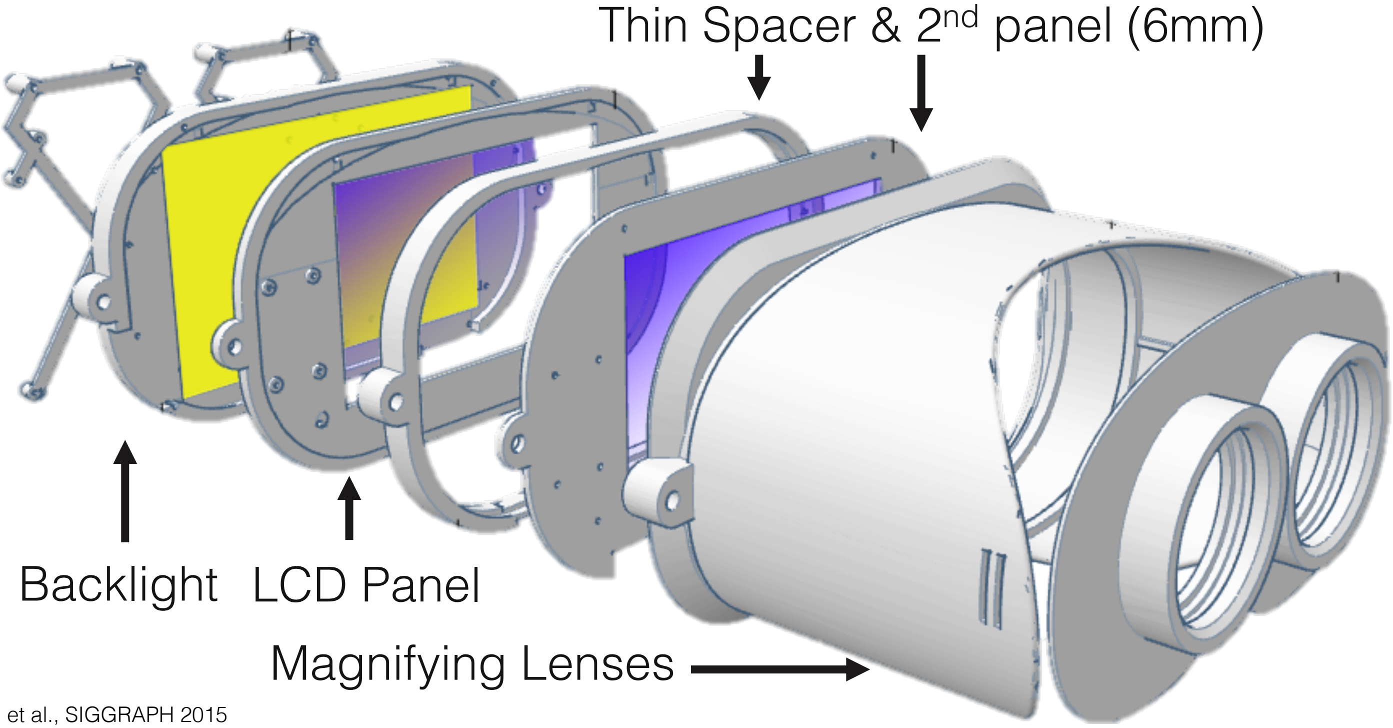


Idea: project multiple different perspectives into different parts of the pupil!

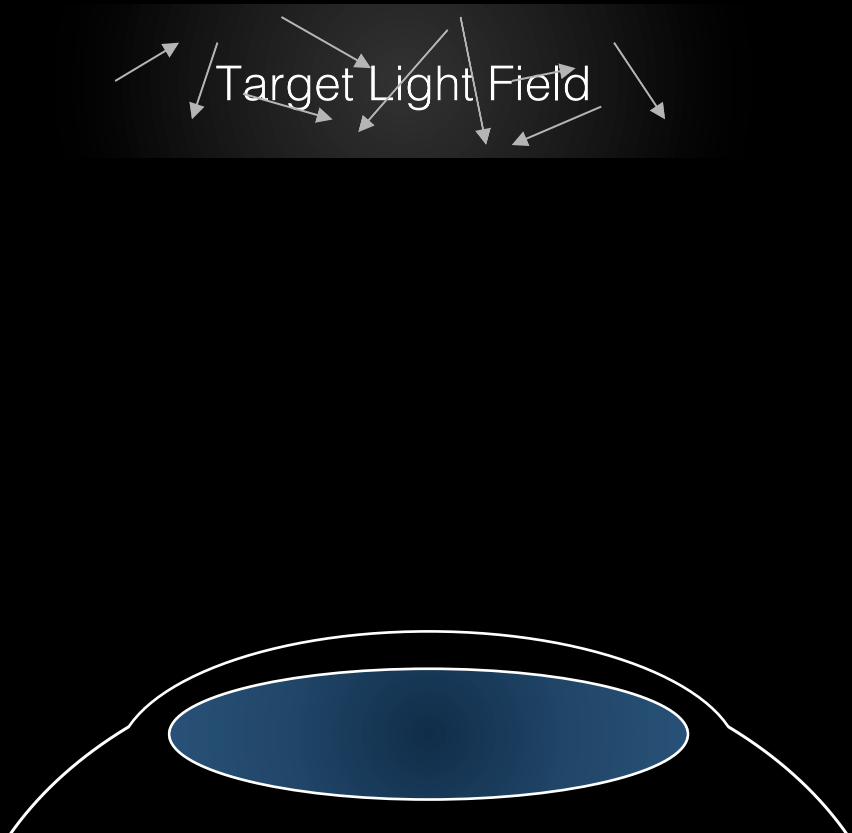
Light Field Stereoscope

Huang et al., SIGGRAPH 2015

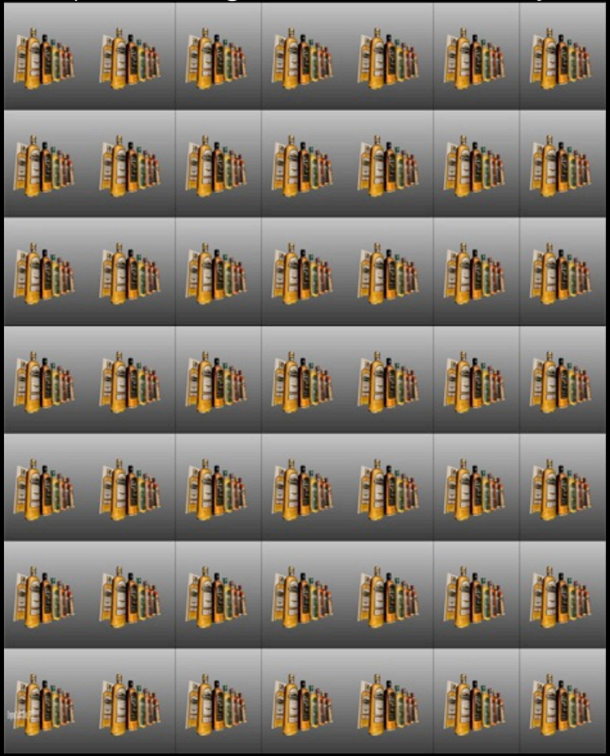
Light Field Stereoscope



Huang et al., SIGGRAPH 2015

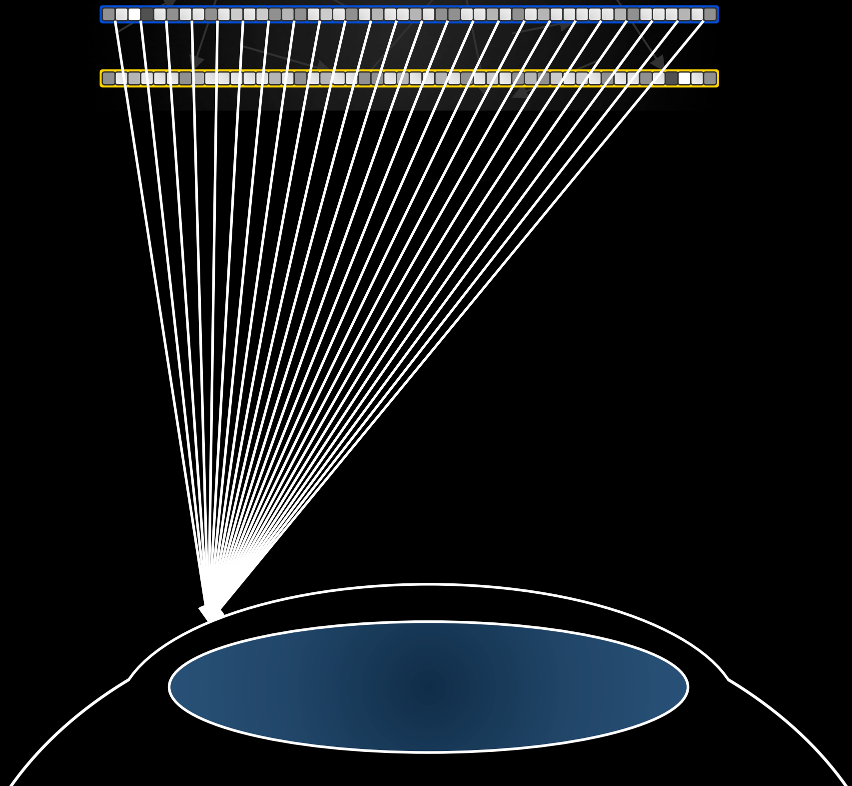


Input: 4D light field for each eye

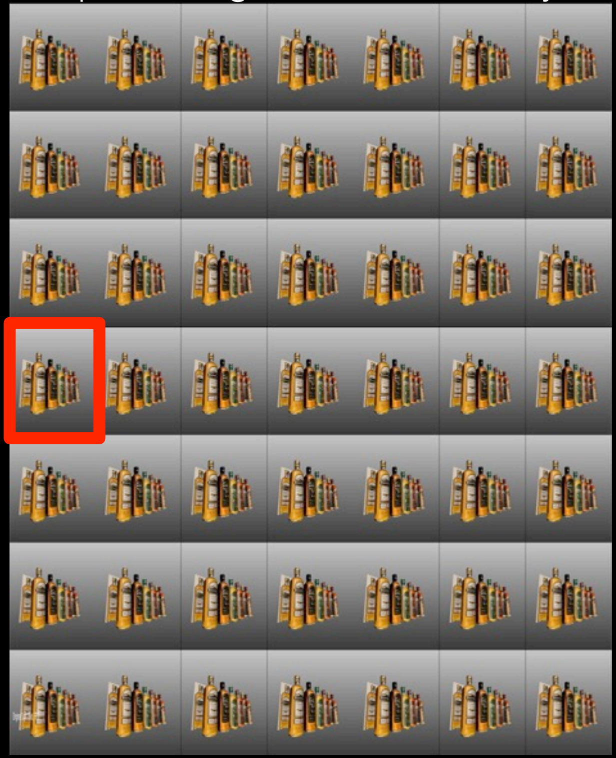


Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation

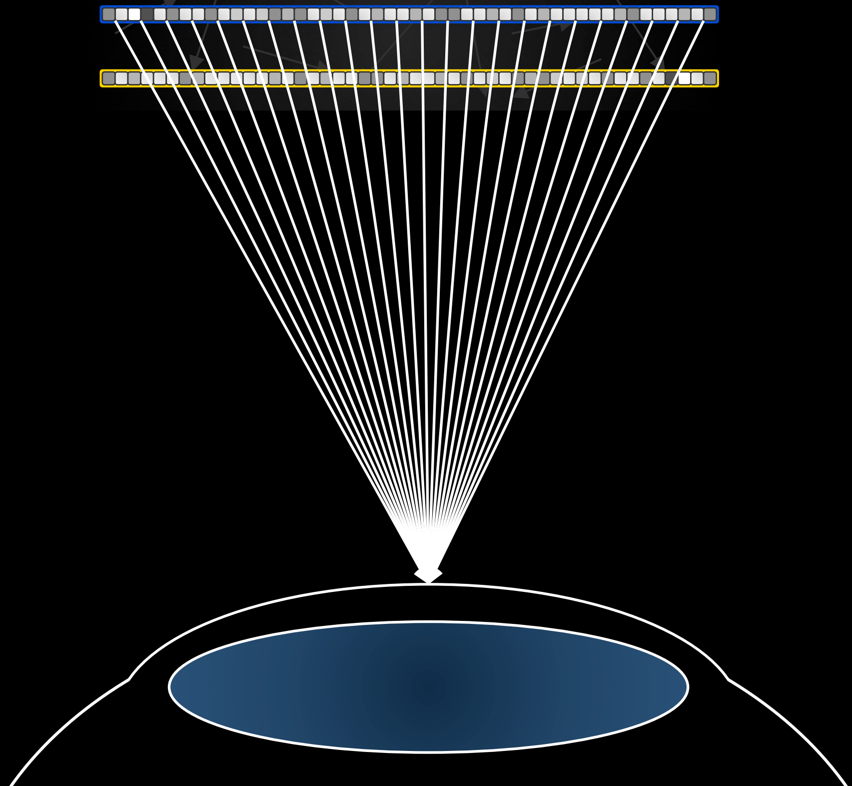


Input: 4D light field for each eye

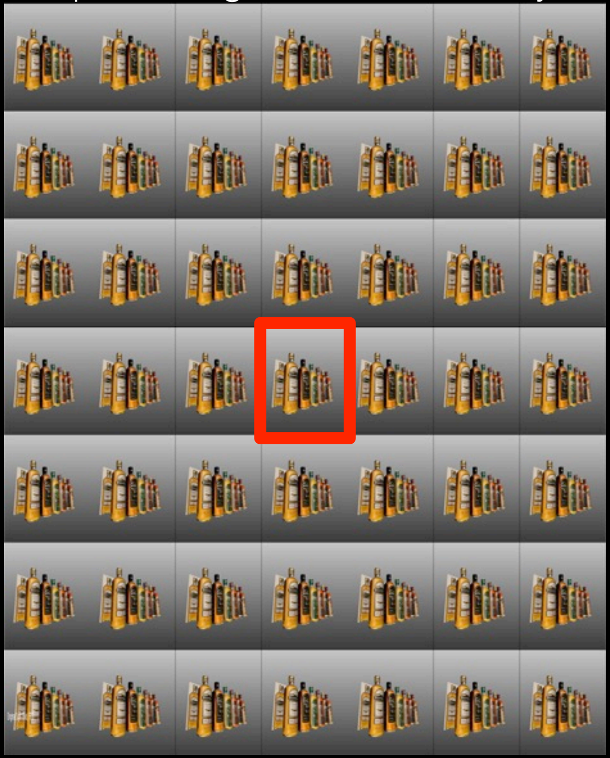


Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation

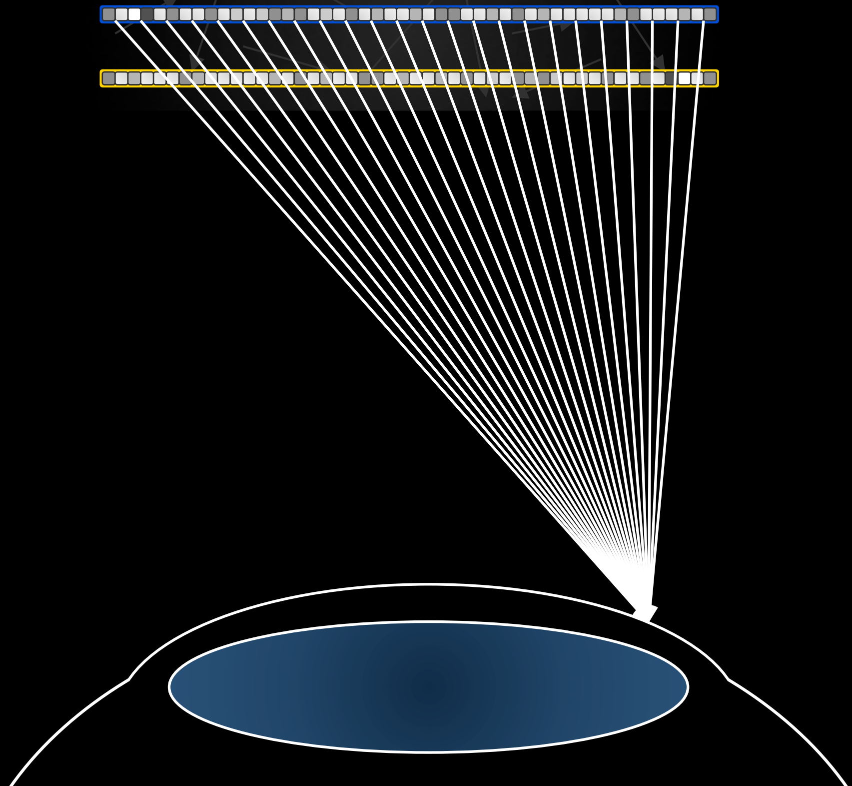


Input: 4D light field for each eye

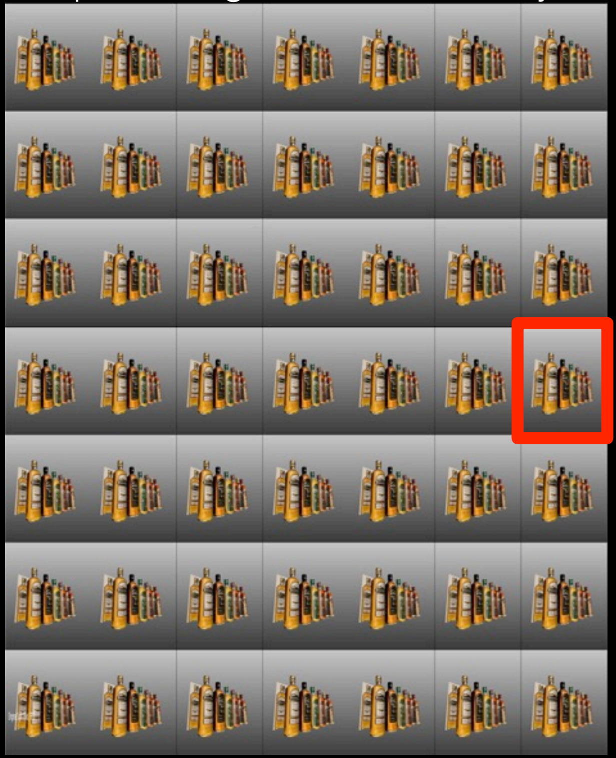


Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation

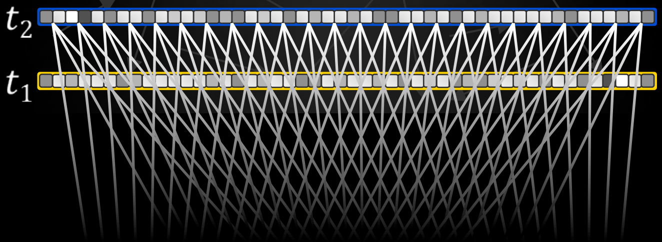


Input: 4D light field for each eye



Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation



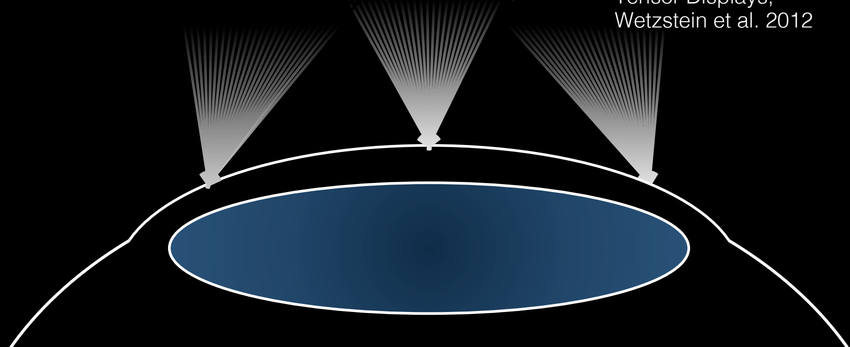
$$\underset{\{t_1, t_2\}}{minimize} \; \|\beta l - (\phi_1 t_1) \circ (\phi_2 t_2)\|^2 \quad s.t.\ 0 \leq t_1, t_2 \leq 1$$

Reconstruction:

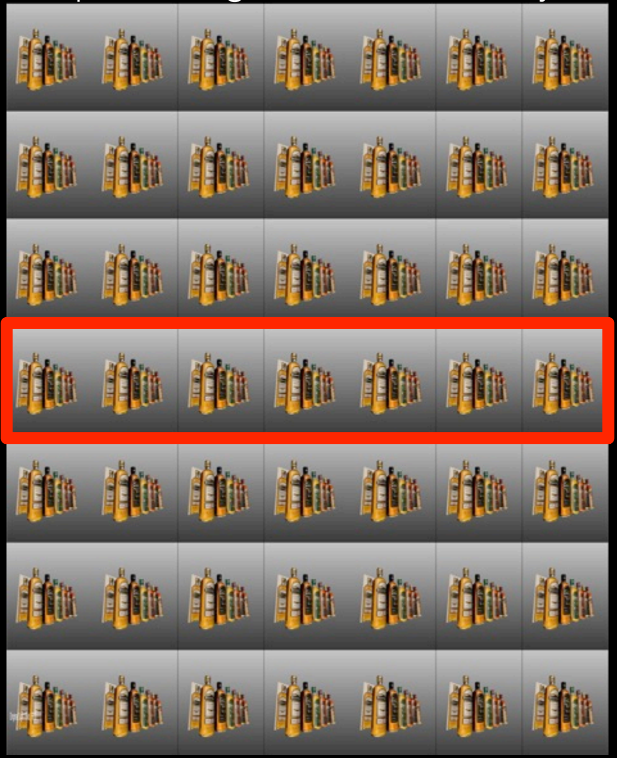
$$t_1 \leftarrow t_1 \circ \frac{\phi_1^T(\beta l \circ (\phi_2 t_2))}{\phi_1^T\left(\tilde{l} \circ (\phi_2 t_2)\right) + \epsilon}$$

for layer t_1

Tensor Displays, Wetzstein et al. 2012

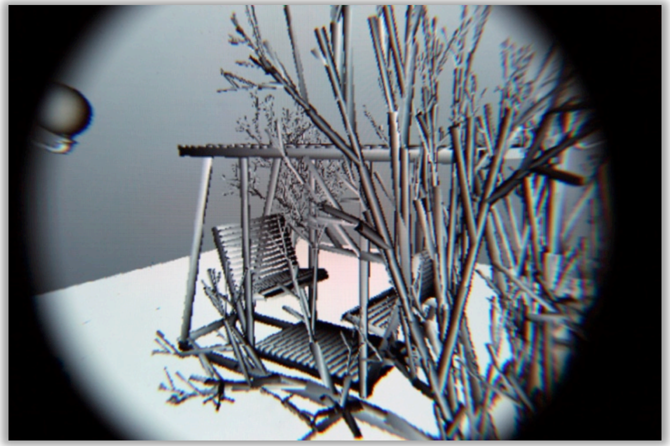


Input: 4D light field for each eye



Model Courtesy of Bushmills Irish Whiskey

Light Field Stereoscope

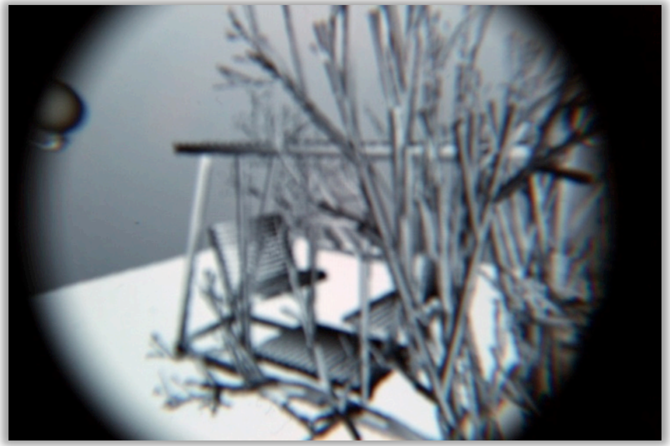


Traditional HMDs
- No Focus Cues

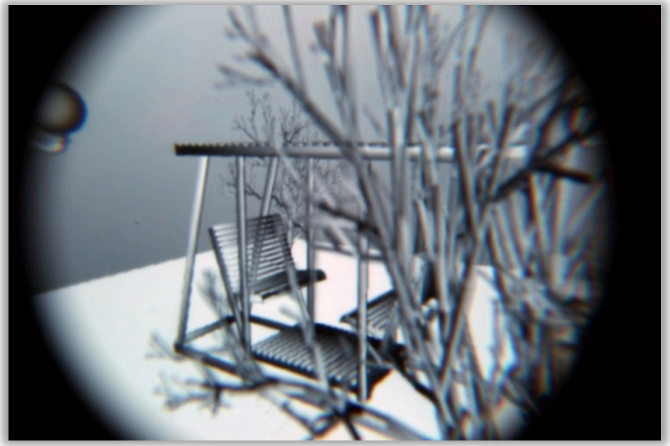
The Light Field HMD
Stereoscope

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



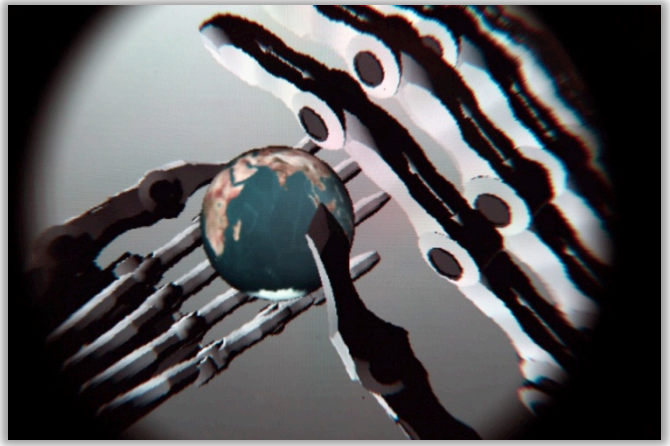
Traditional HMDs
- No Focus Cues



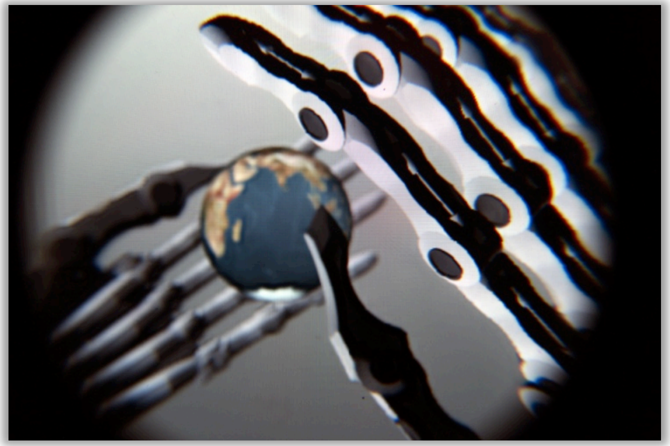
The Light Field HMD
Stereoscope

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



Traditional HMDs
- No Focus Cues

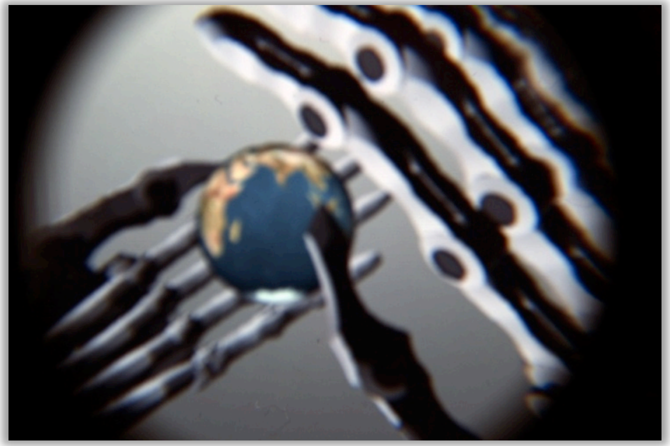


The Light Field HMD
Stereoscope

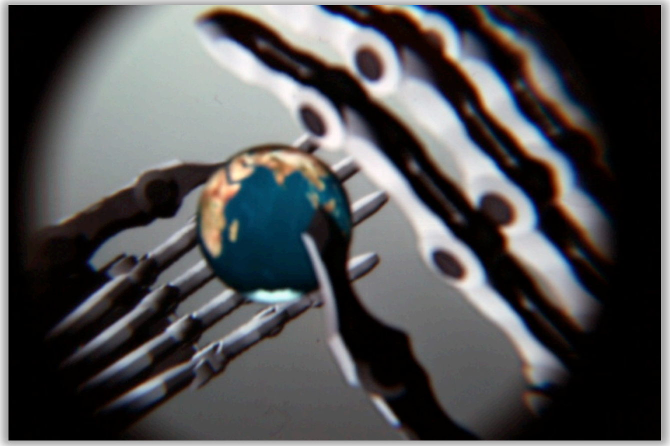
Model Courtesy of Paul H. Manning

Huang et al., SIGGRAPH 2015

Light Field Stereoscope



Traditional HMDs
- No Focus Cues

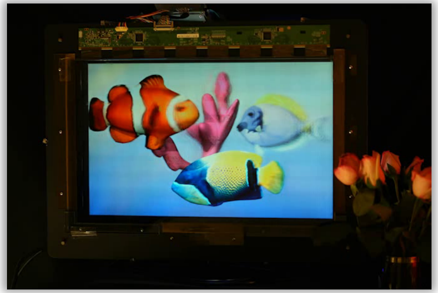


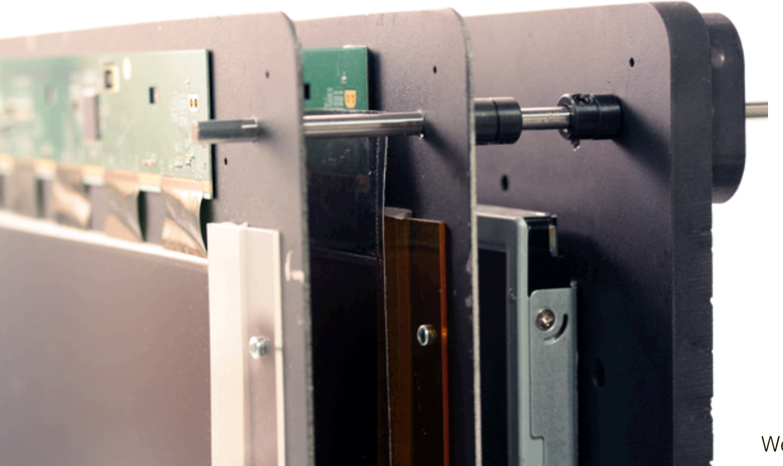
The Light Field HMD
Stereoscope

Model Courtesy of Paul H. Manning

Huang et al., SIGGRAPH 2015

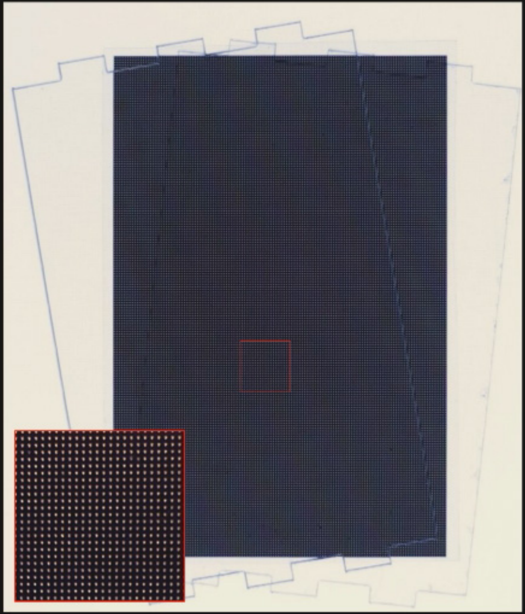
Tensor Displays

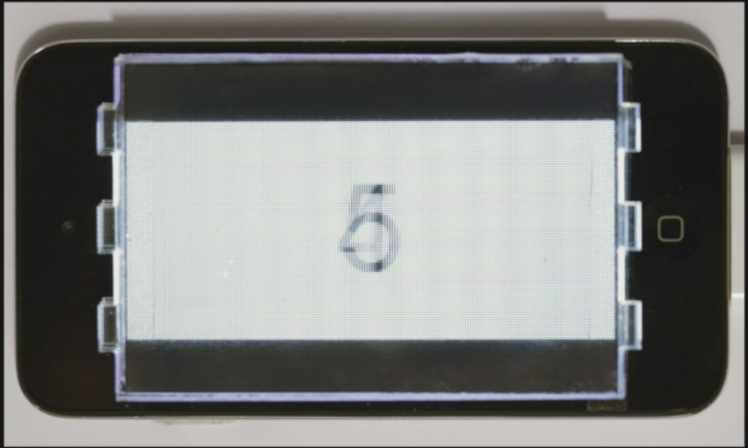


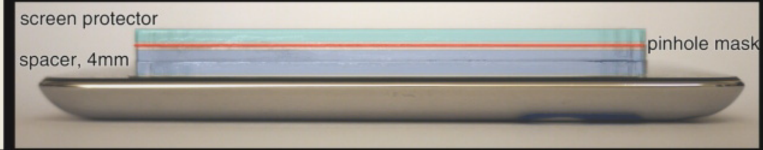


Wetzstein et al., SIGGRAPH 2012

Vision-correcting Display







printed transparency

iPod Touch prototype

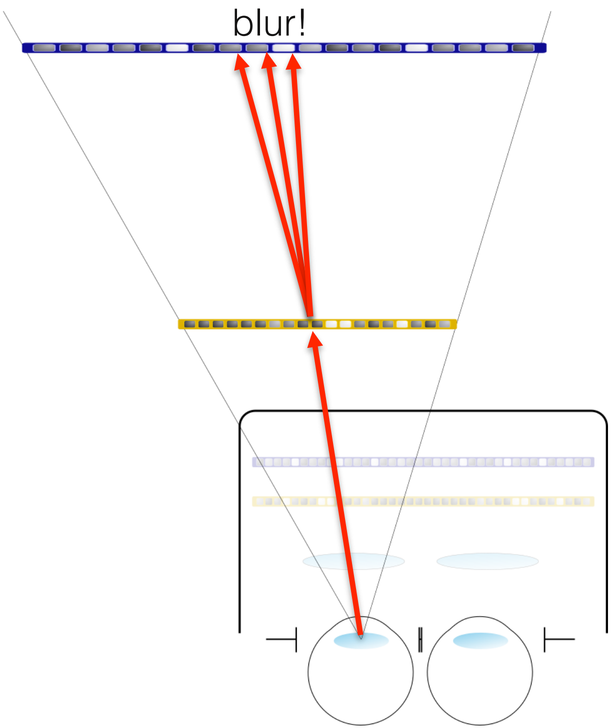
Huang et al., SIGGRAPH 2014

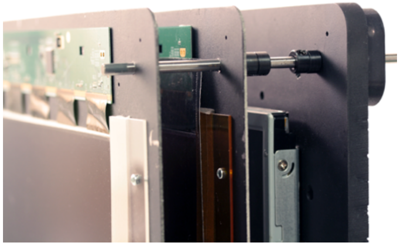
300 dpi or higher

prototype

Huang et al., SIGGRAPH 2014

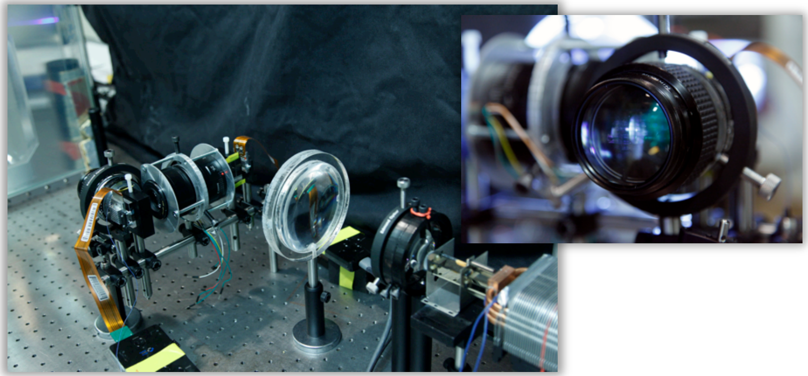
Diffraction in Multilayer Light Field Displays





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

Less diffraction artifacts with LCoS



Hirsch et al, SIGGRAPH 2014

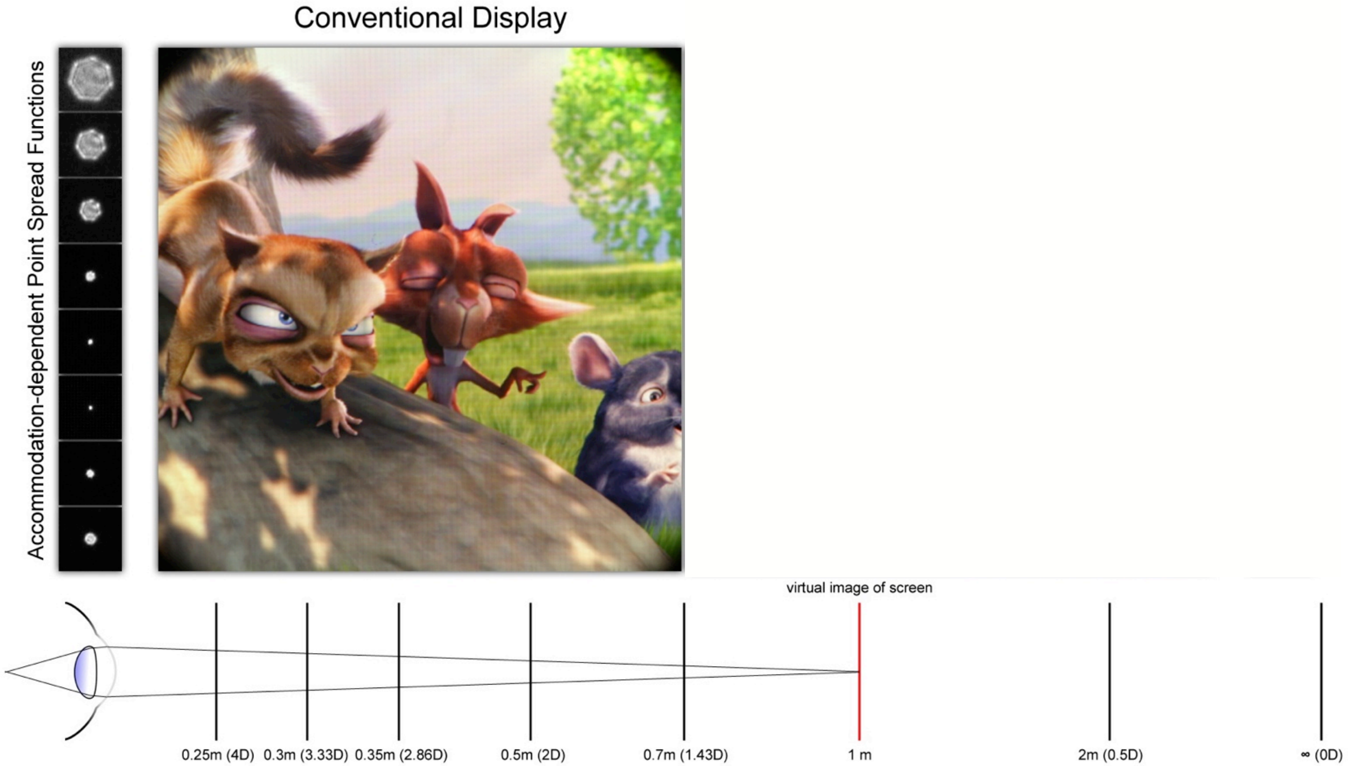
…

more details in separate part on light fields after the rest (ppt is getting too big and keeps crashing)

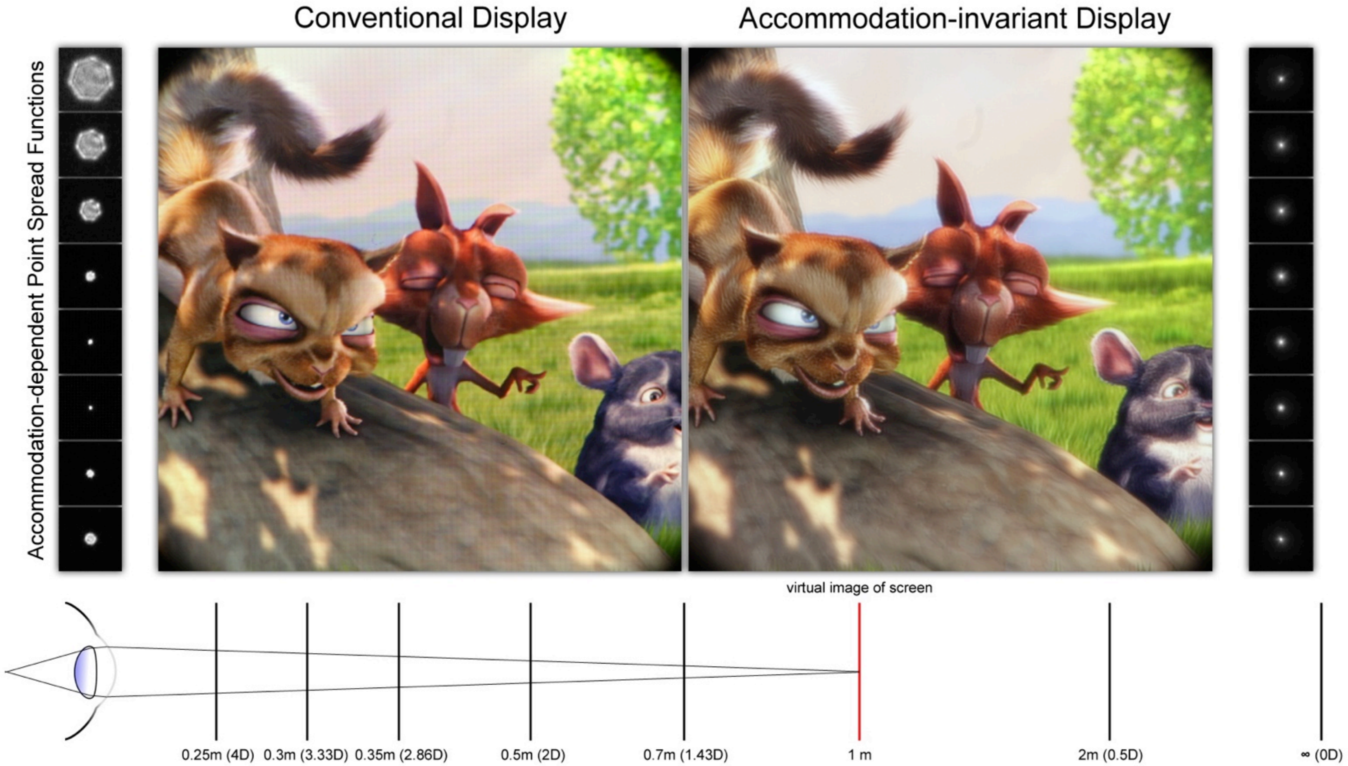
…

3. Accommodation-invariant Near-eye Displays

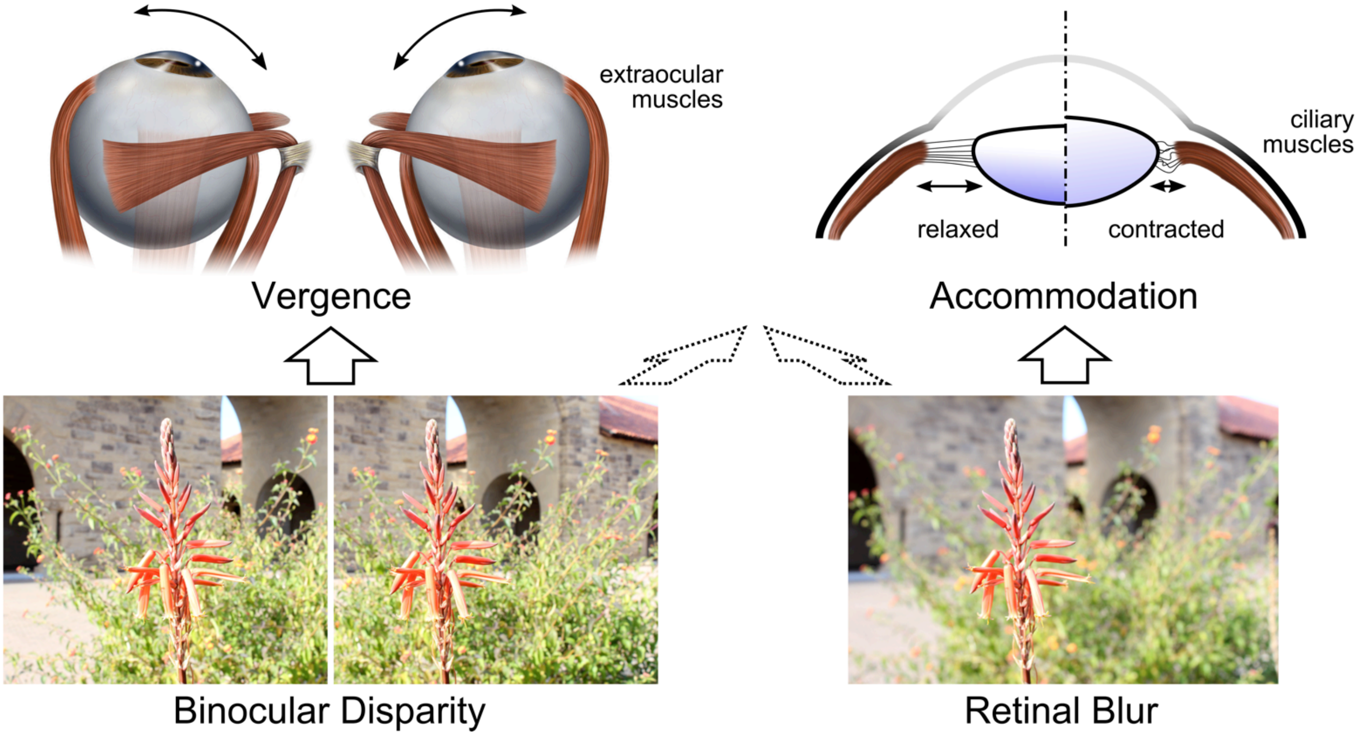
Blur Gradient Driven Accommodation



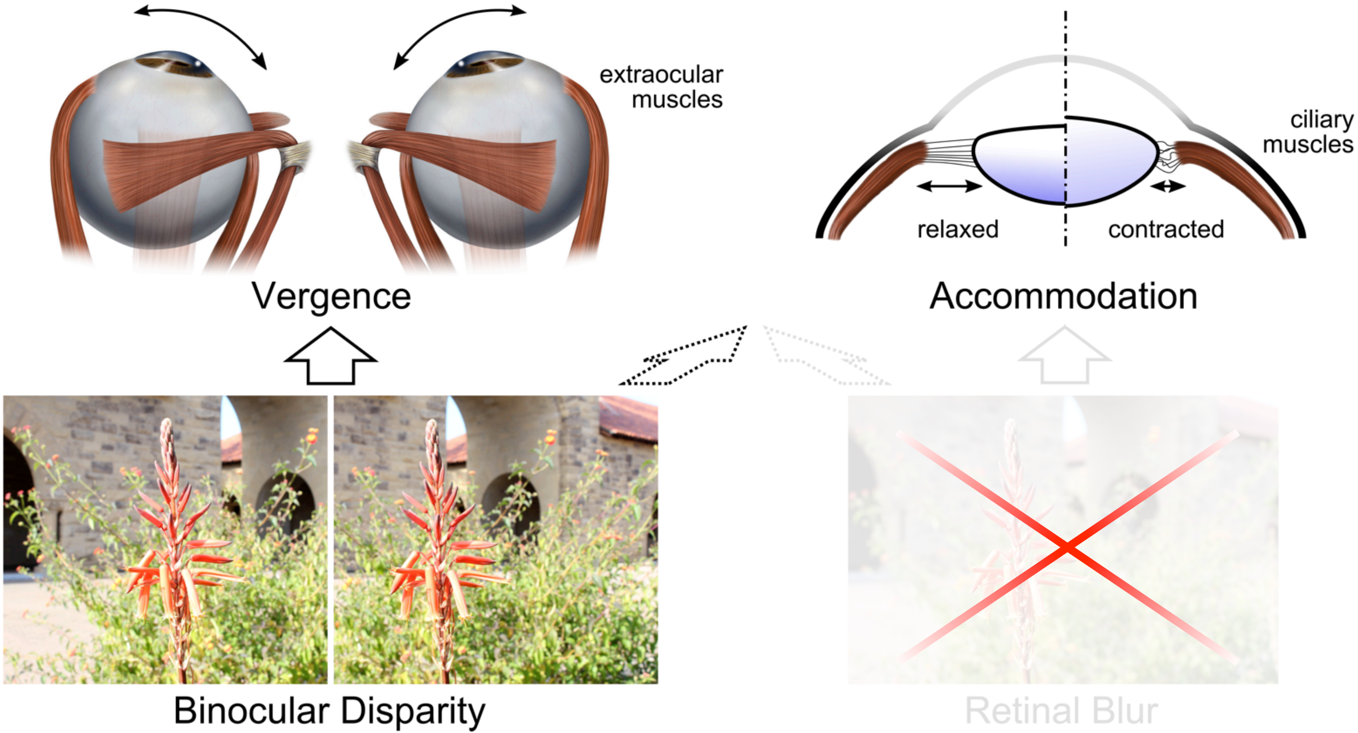
PSF Engineering

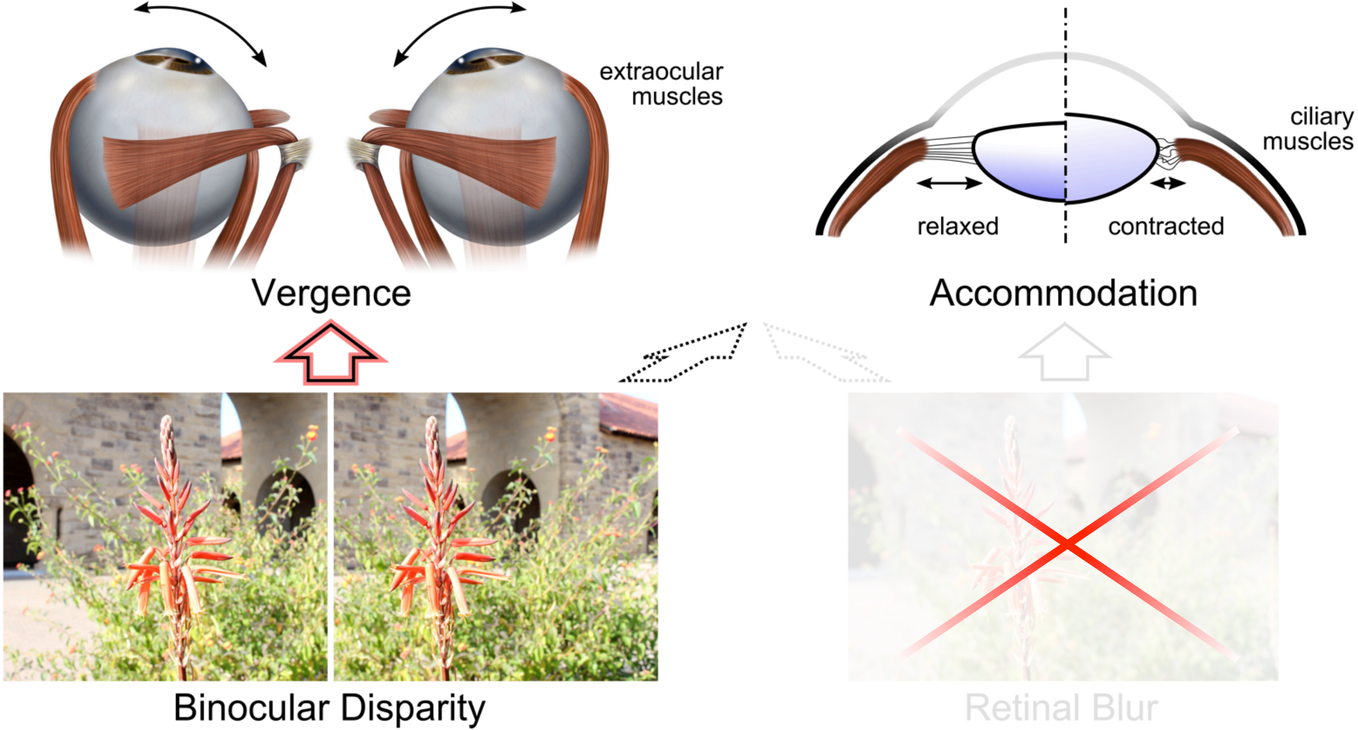


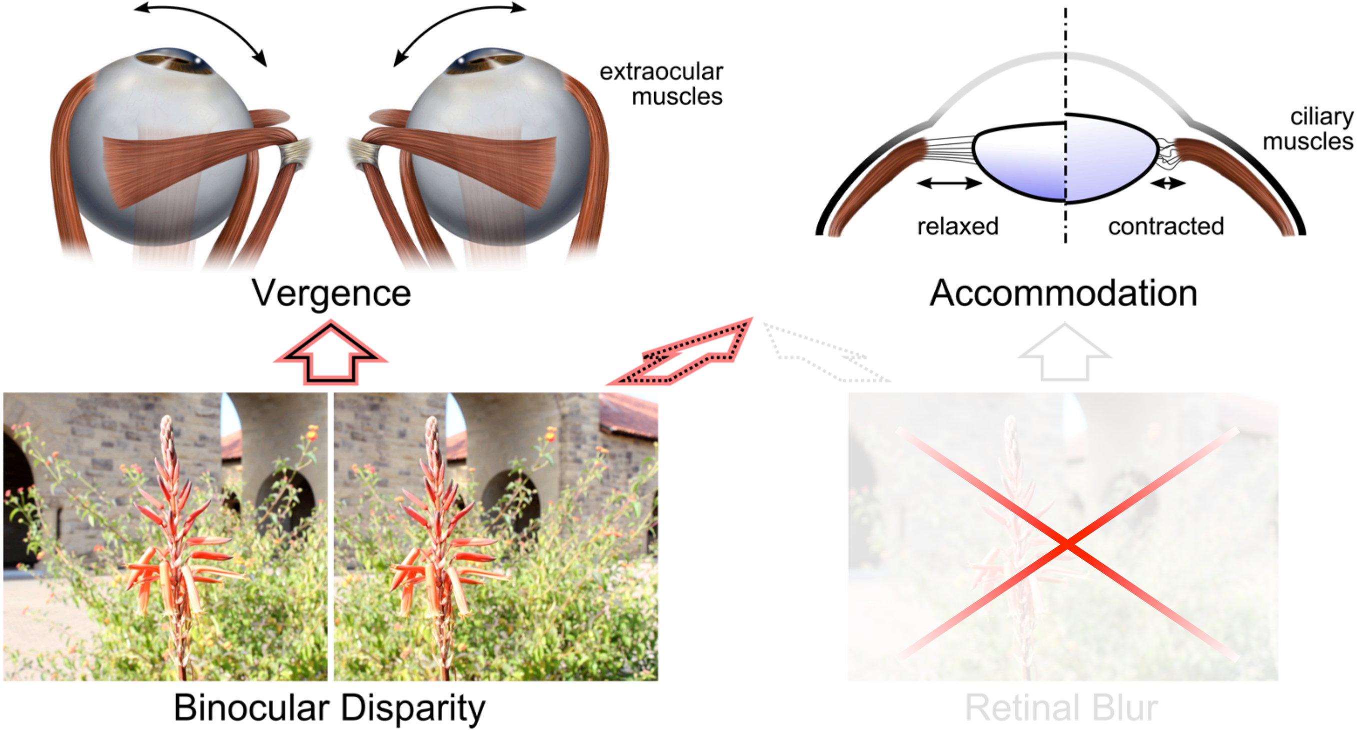
Q: can we drive accommodation with stereoscopic cues by optically removing the retinal blur cue?



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
Vergence
ciliary
muscles
relaxed
contracted
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

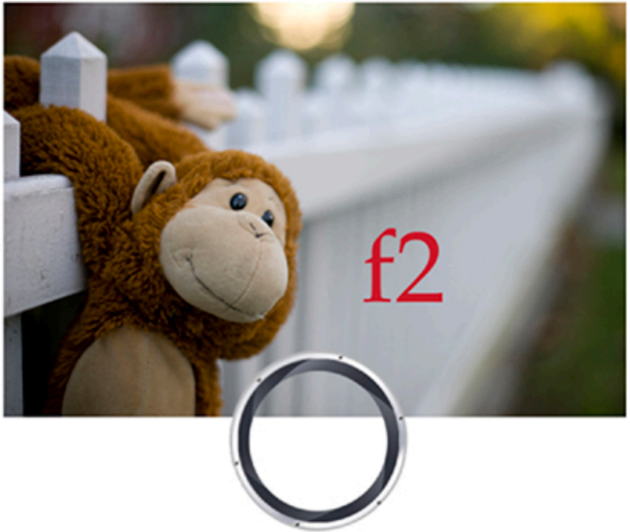


Image courtesy of Concept One Studios

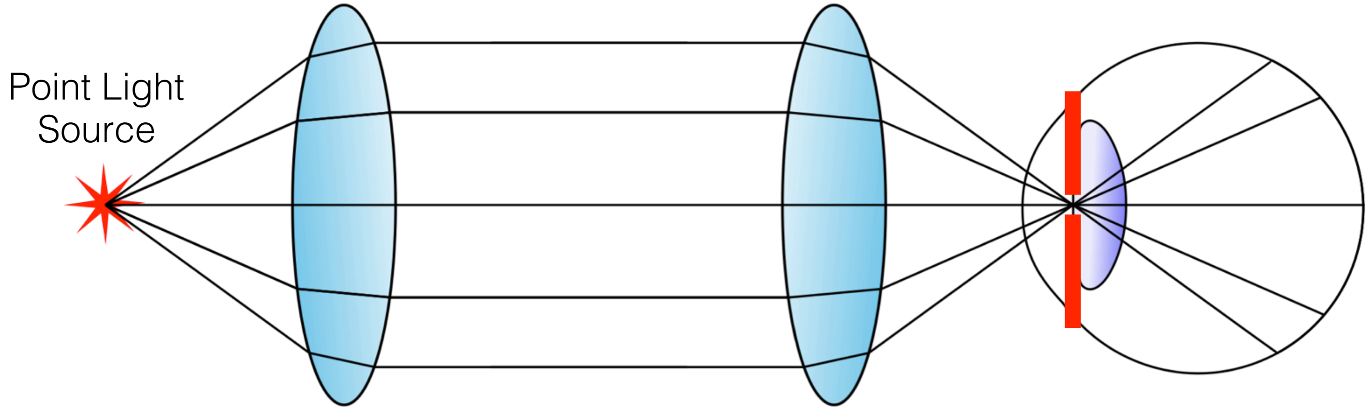
Aperture Controls Depth of Field

Image courtesy of Concept One Studios

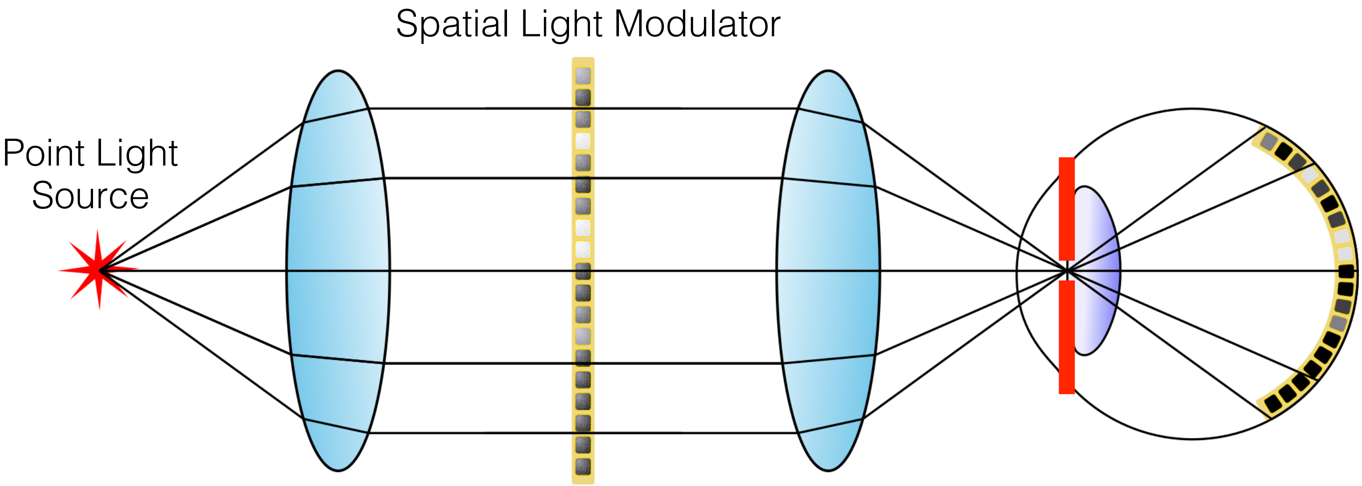
Aperture Controls Depth of Field

Image courtesy of Concept One Studios

Maxwellian-type (pinhole) Near-eye Displays

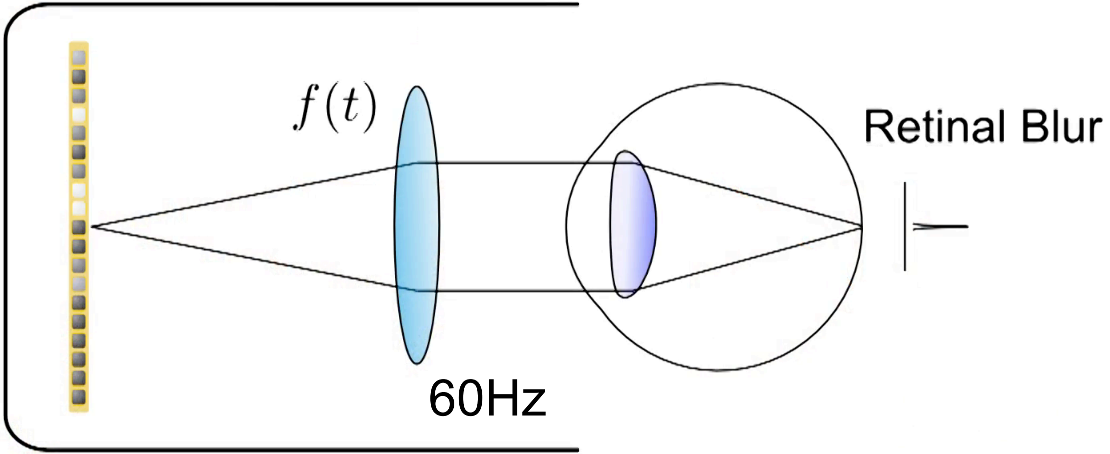


Maxwellian-type (pinhole) Near-eye Displays

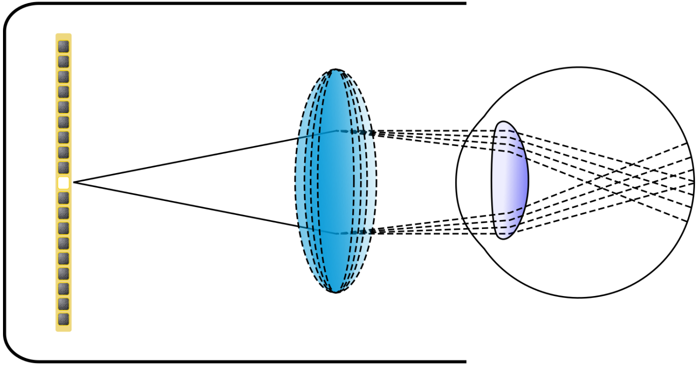


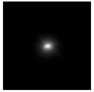
Severely reduces eyebox; requires dynamic steering of exit pupil

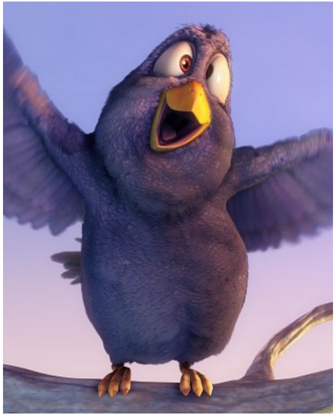
Focal Sweep

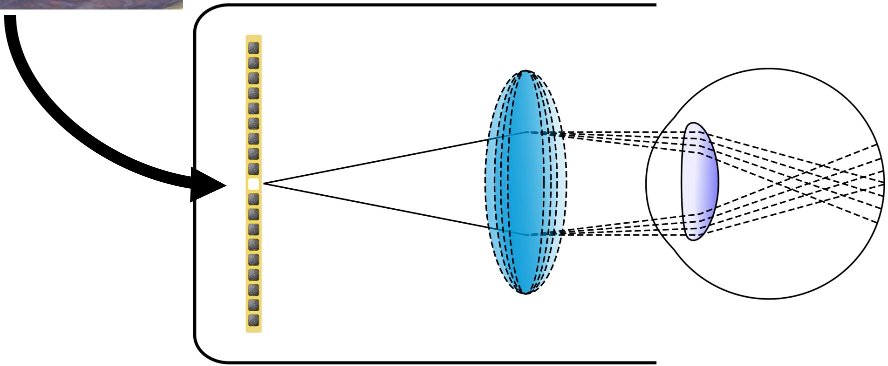


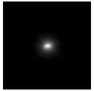
EDOF Cameras:
Dowski & Cathey, App. Opt. 1995
Nagahara et al., ECCV 2008
Cossairt et al., SIGGRAPH 2010



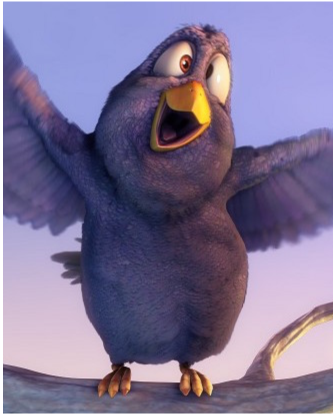








Convolution



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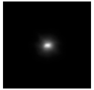
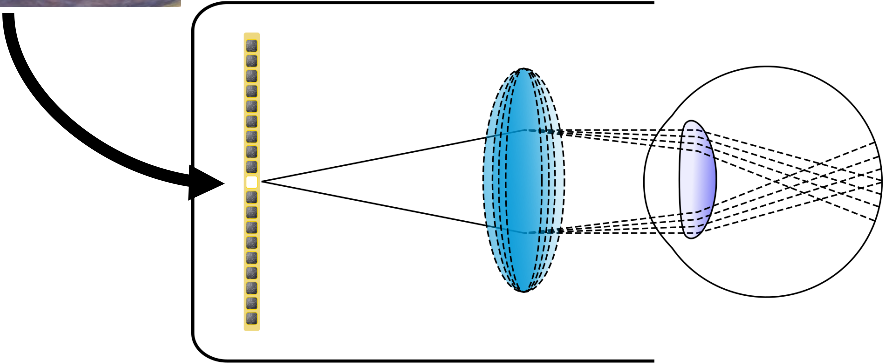
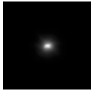
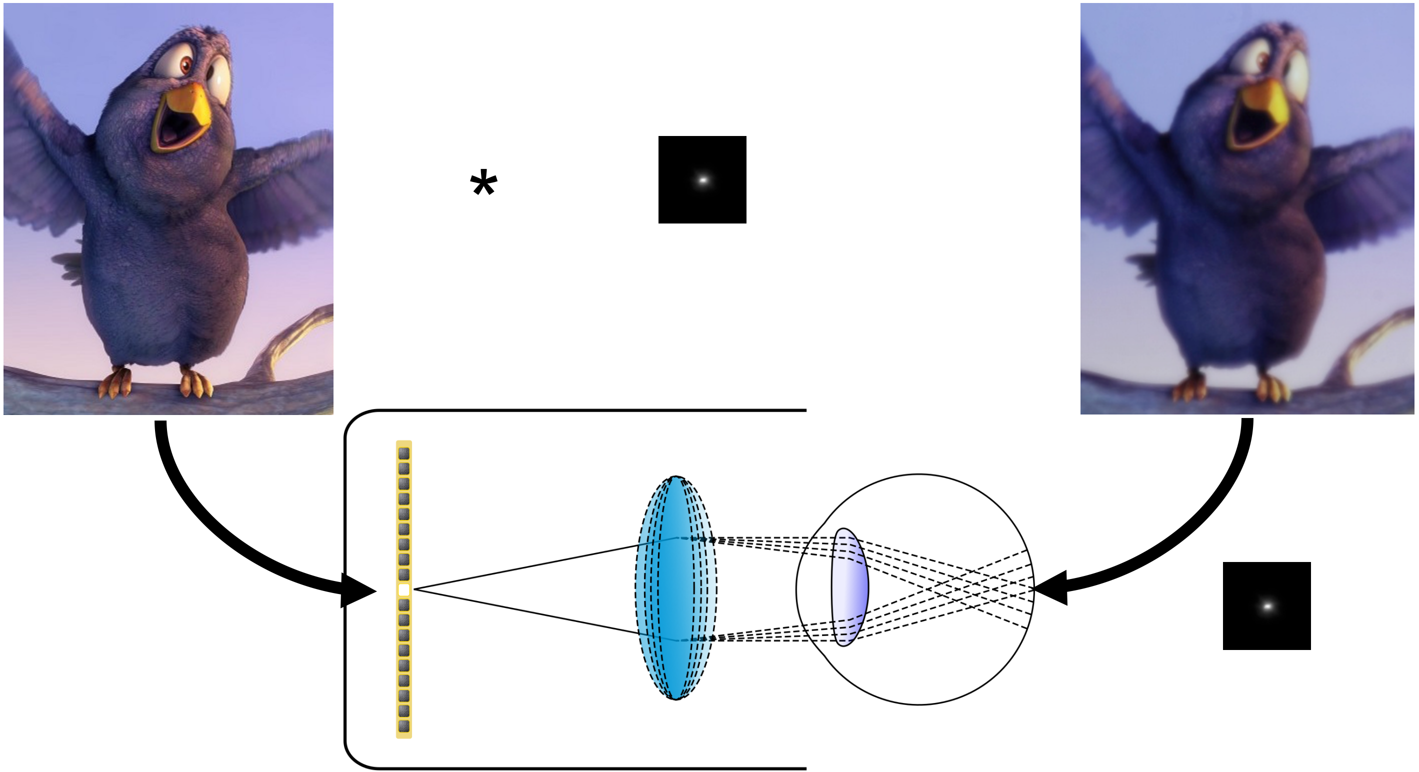


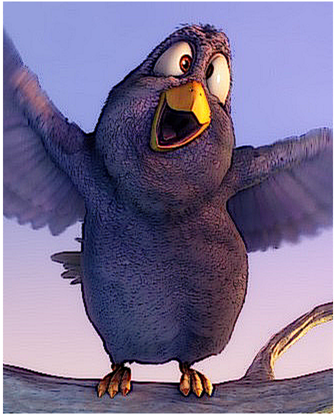




Convolution



Deconvolution



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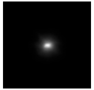

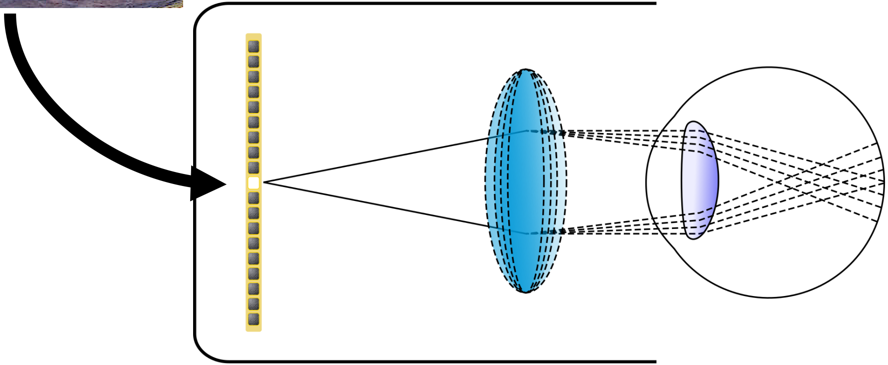

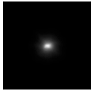

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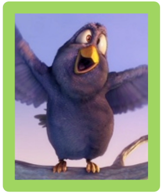
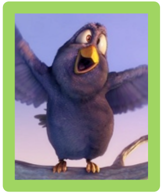
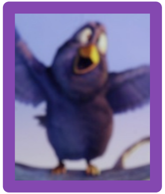


Target Image

Target

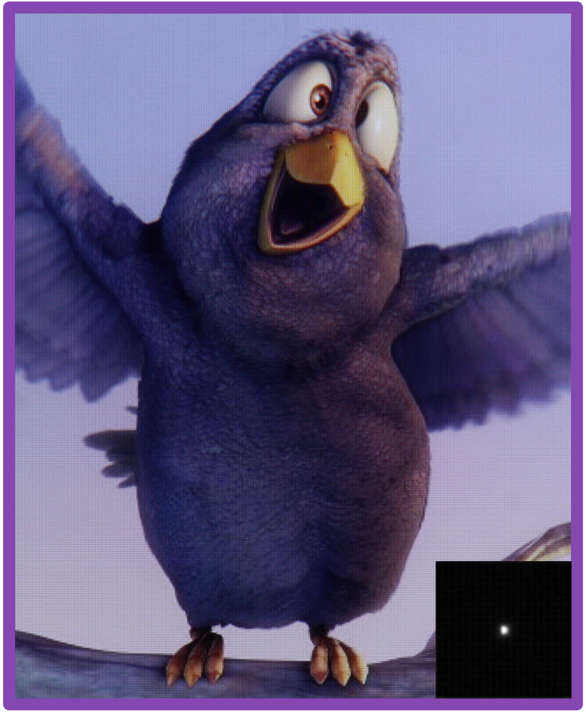


Conventional

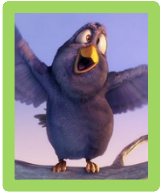


Target Image

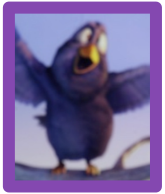
Conventional Display @ 1D



Target

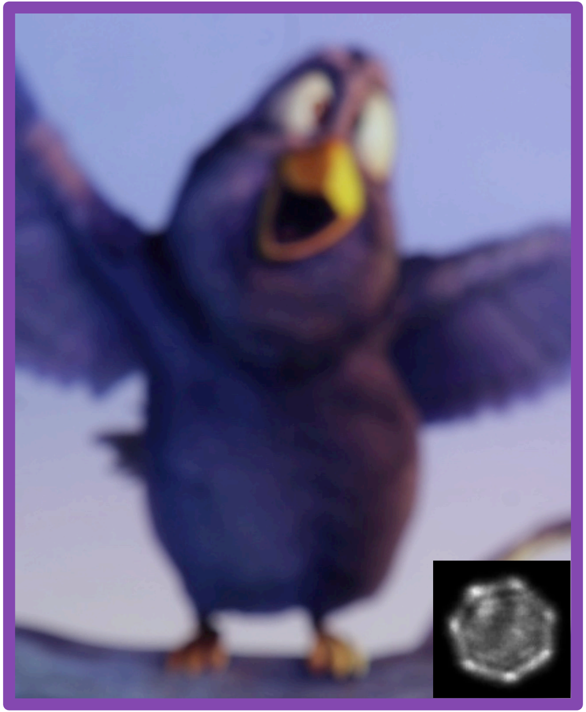


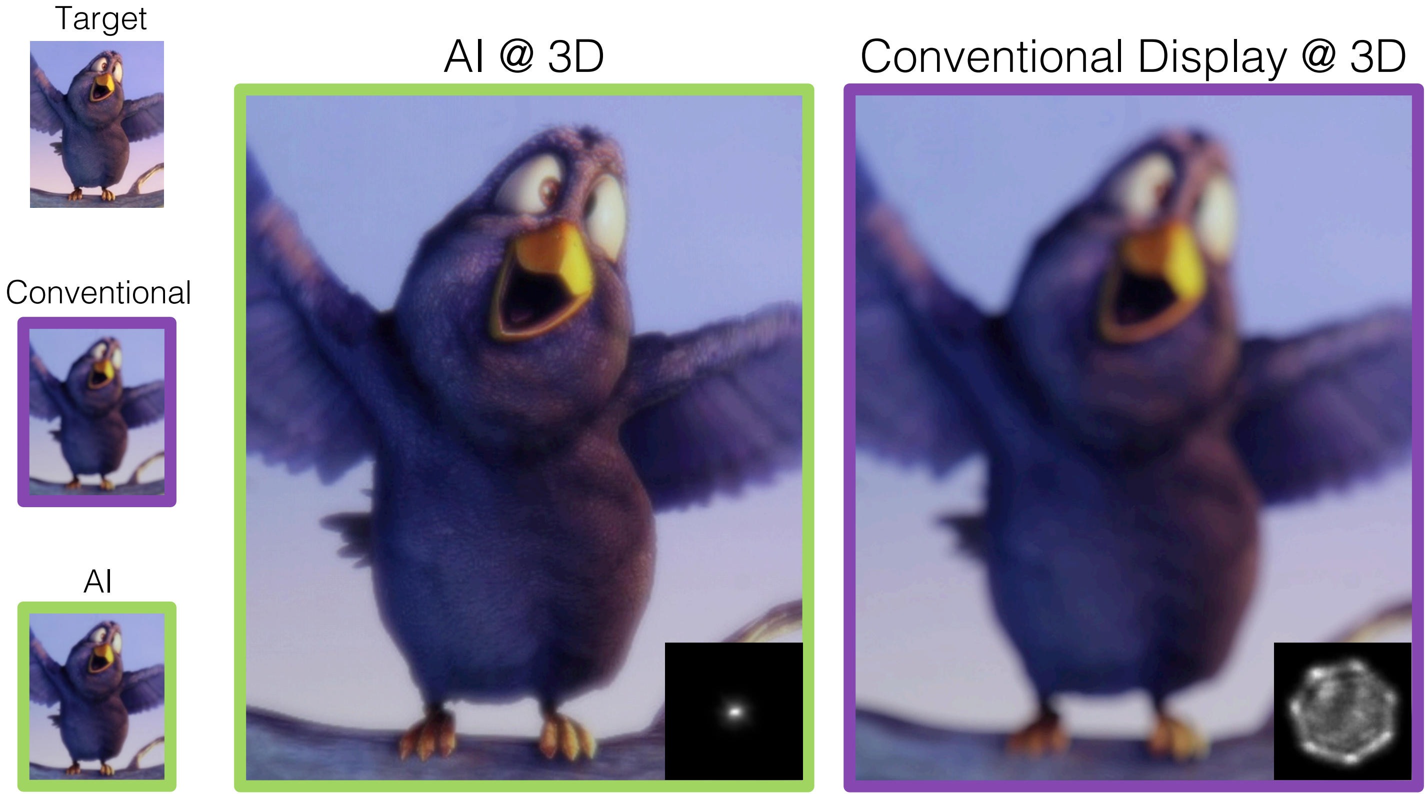
Conventional

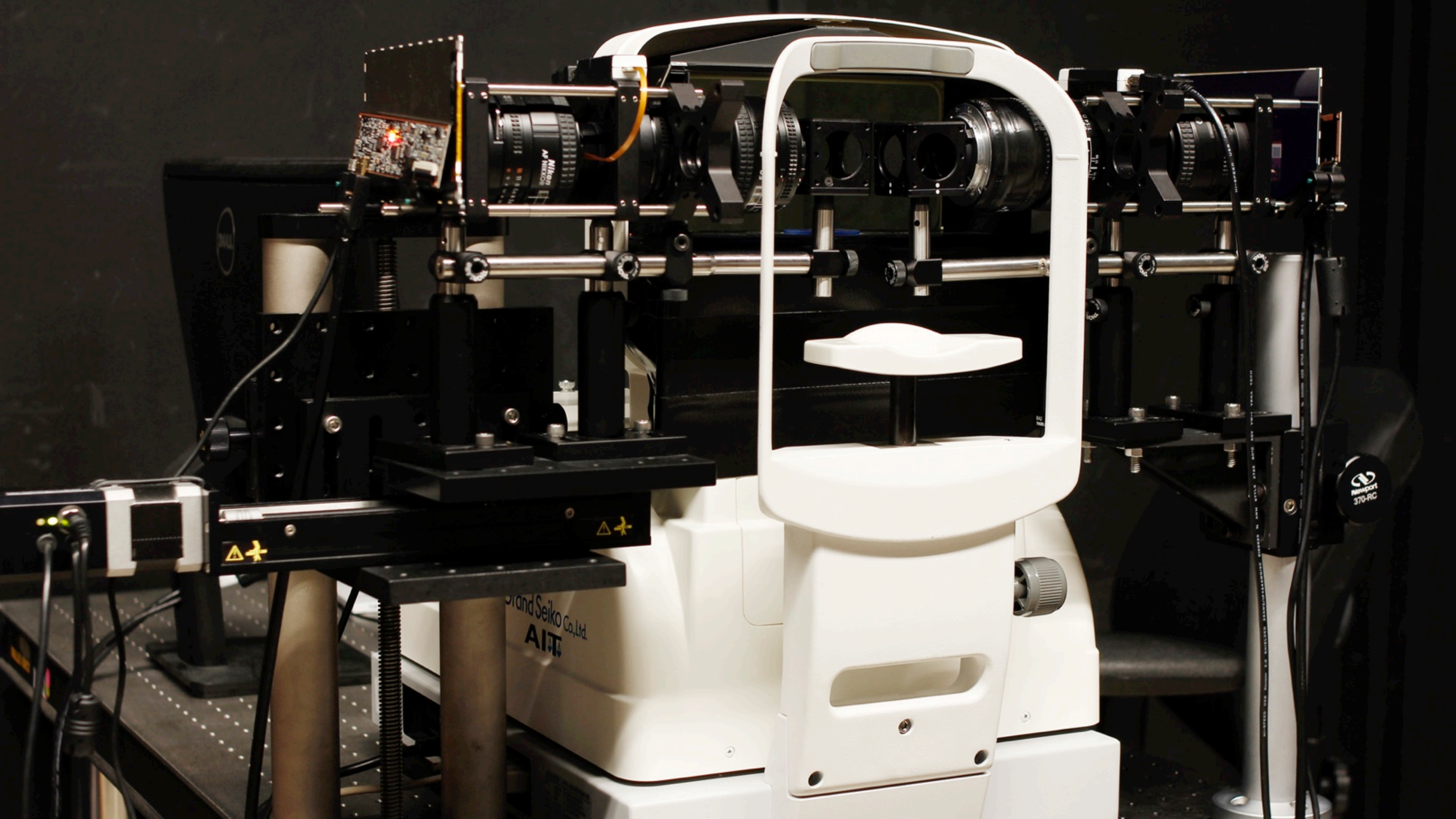


Target Image

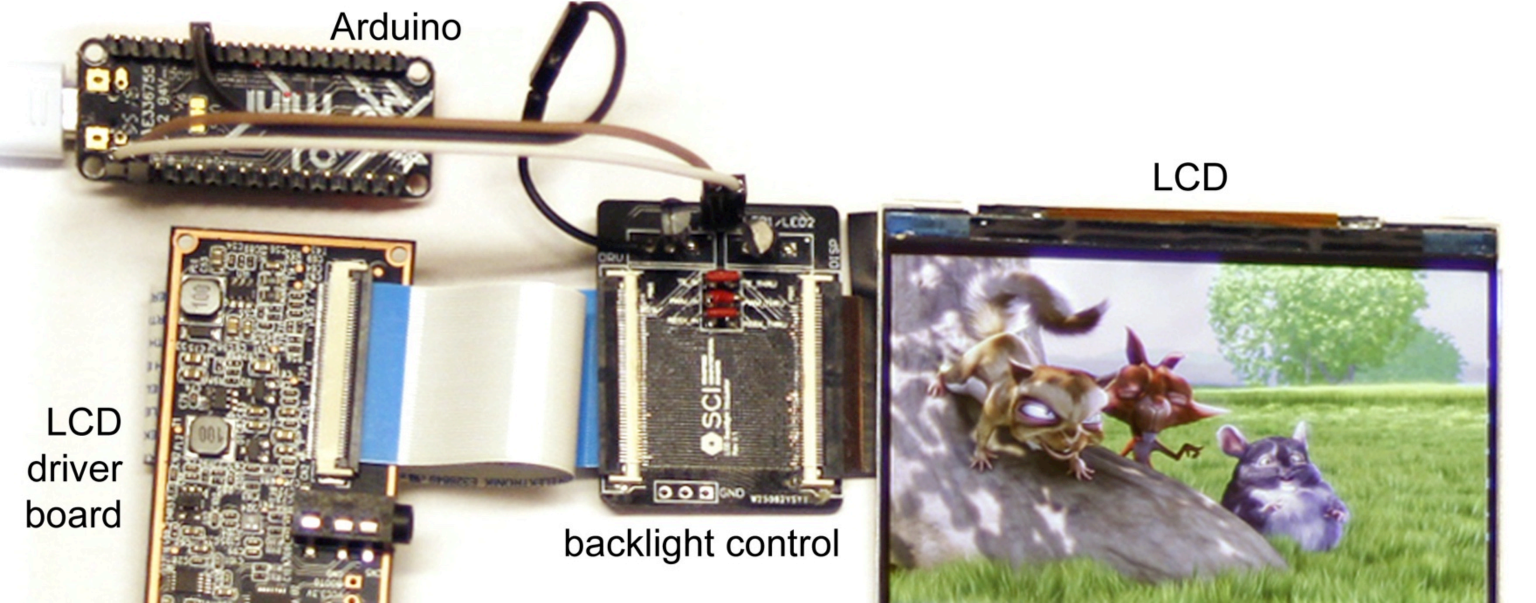
Conventional Display @ 3D




Target
Conventional
AI
AI @ 3D
Conventional Display @ 3D


Nikon
AF NIKKOR
Seiko Co.,Ltd.
AIT
Newport
370-RC

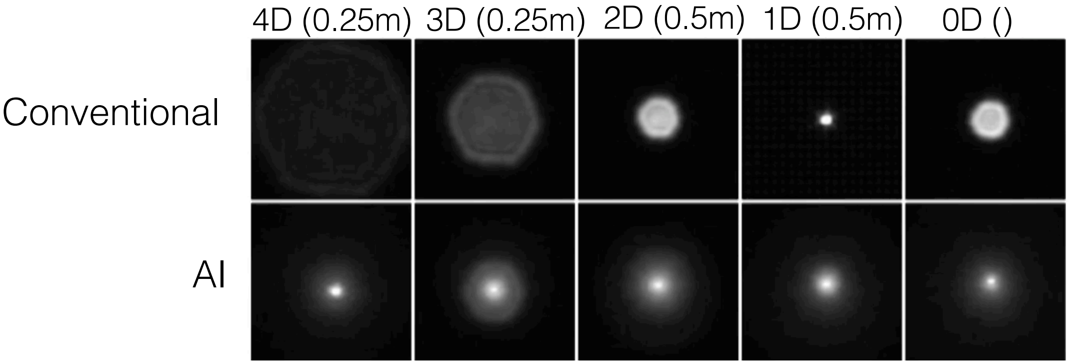
Strobing the Backlight



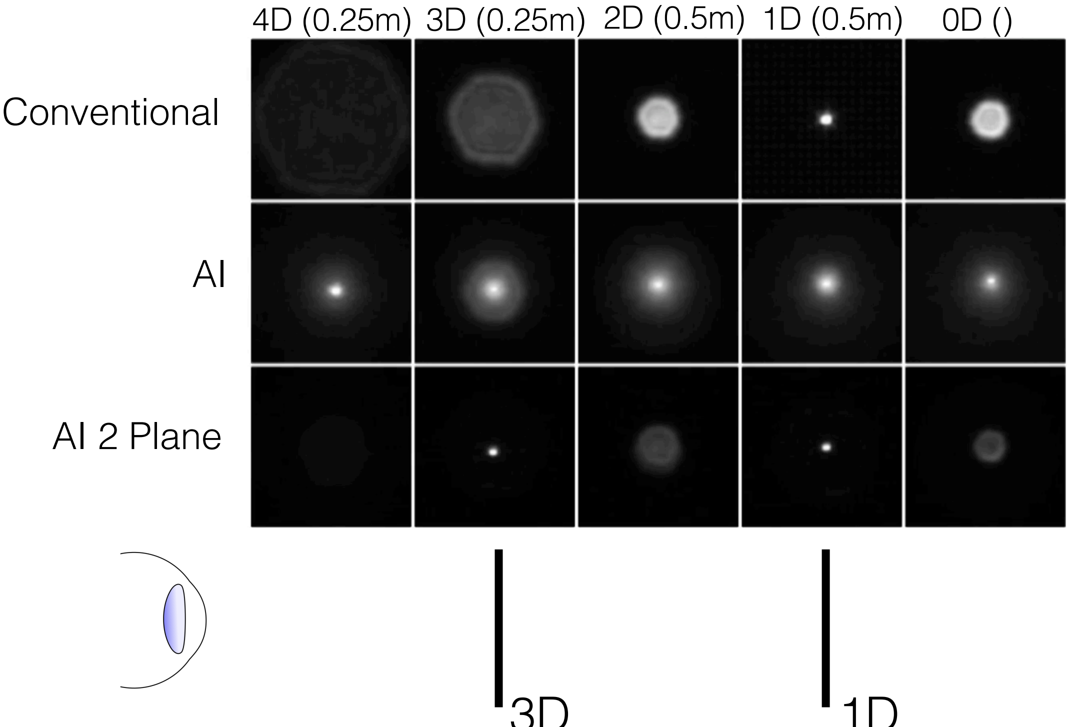
Accommodation Invariant

Multi-plane Accommodation Invariant

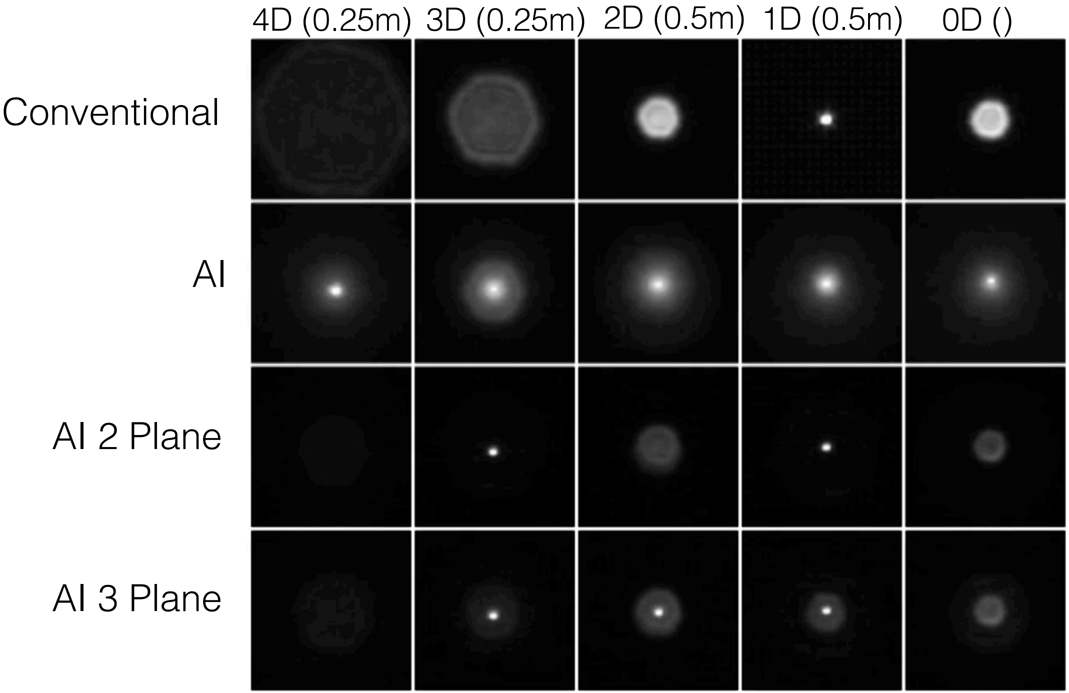
Point Spread Functions

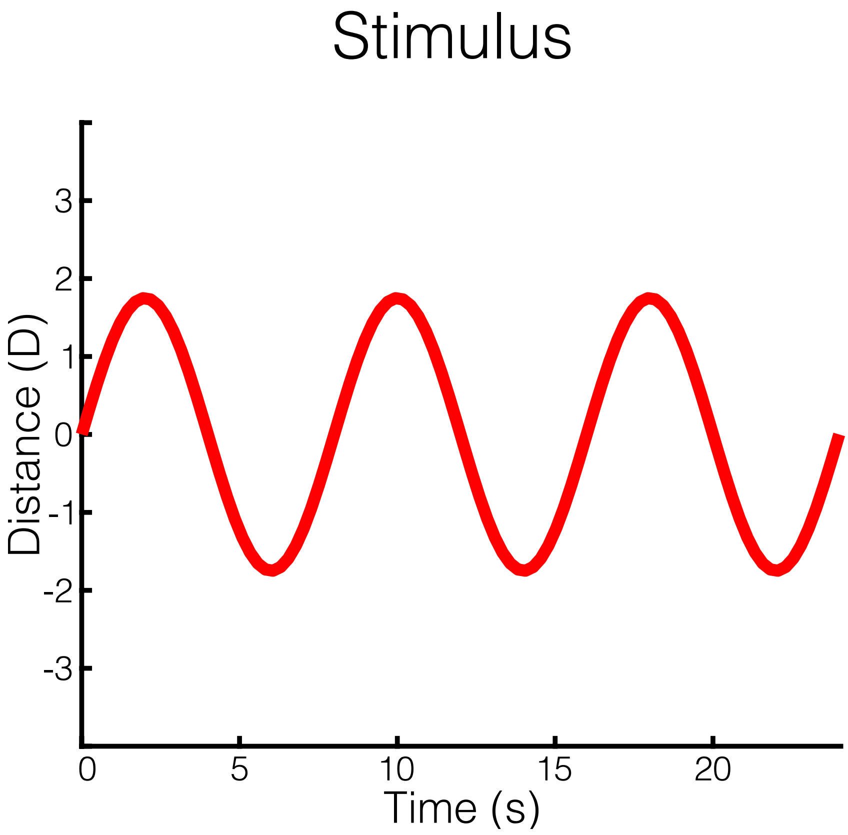


Point Spread Functions

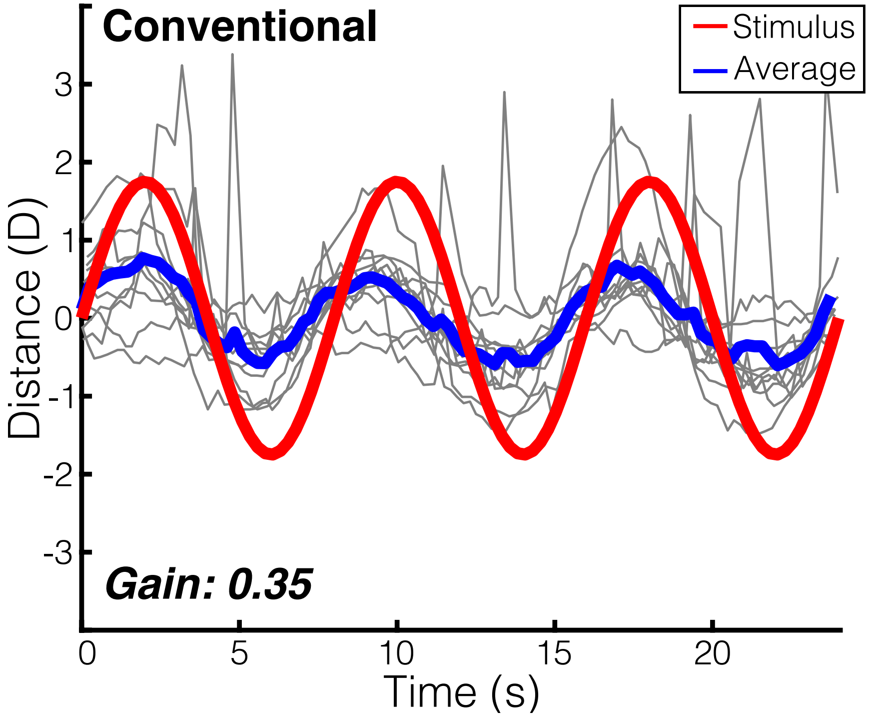


Point Spread Functions

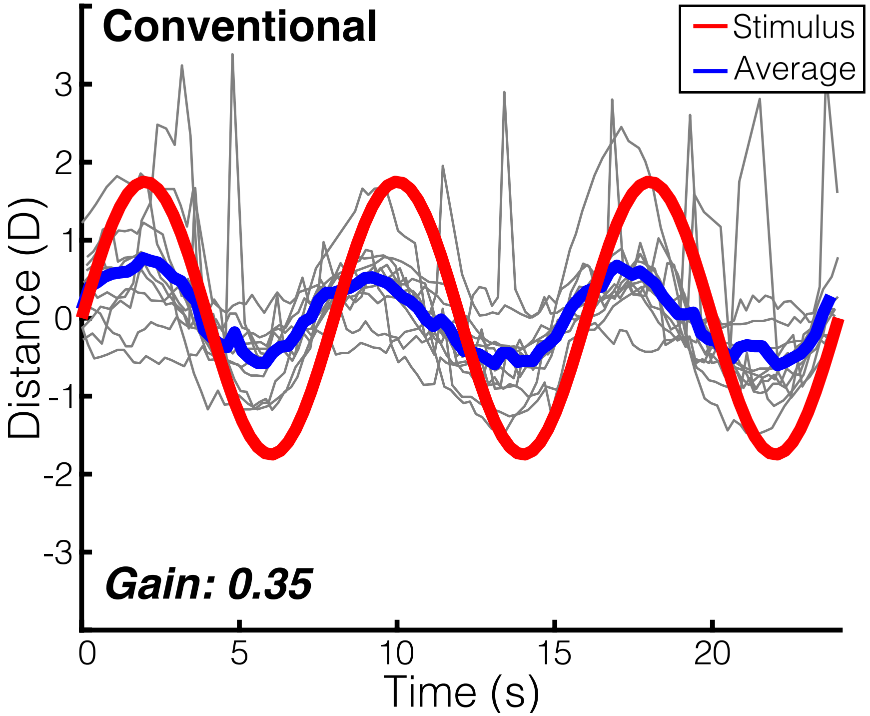



Stimulus
3
2
1
0
-1
-2
-3
Distance (D)
0
5
10
15
20
Time (s)

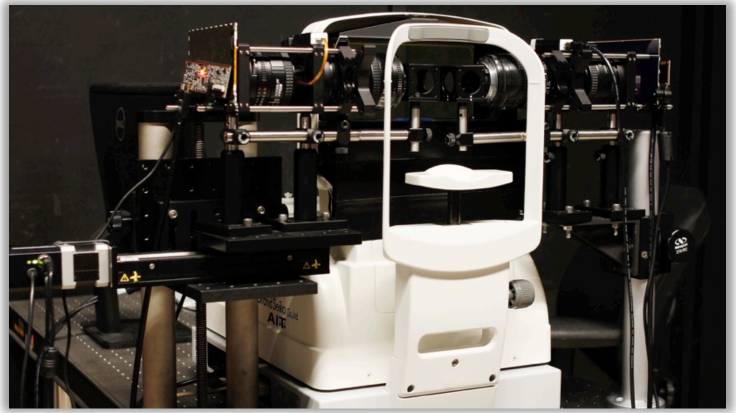
Measured User Response



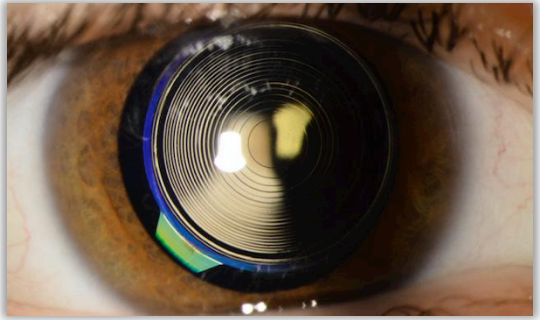
Measured User Response

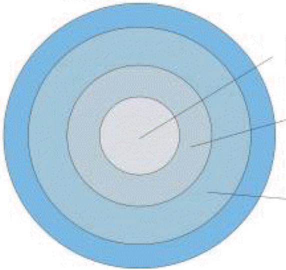


Now: benchtop



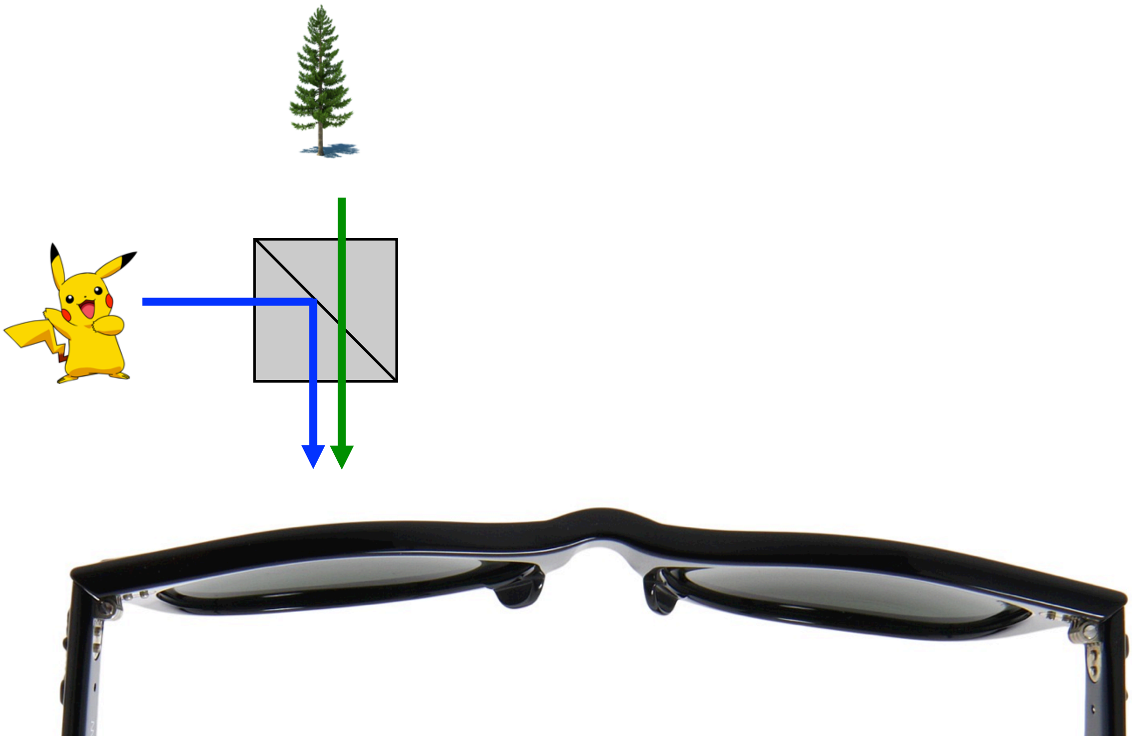
Future: multifocal lenses



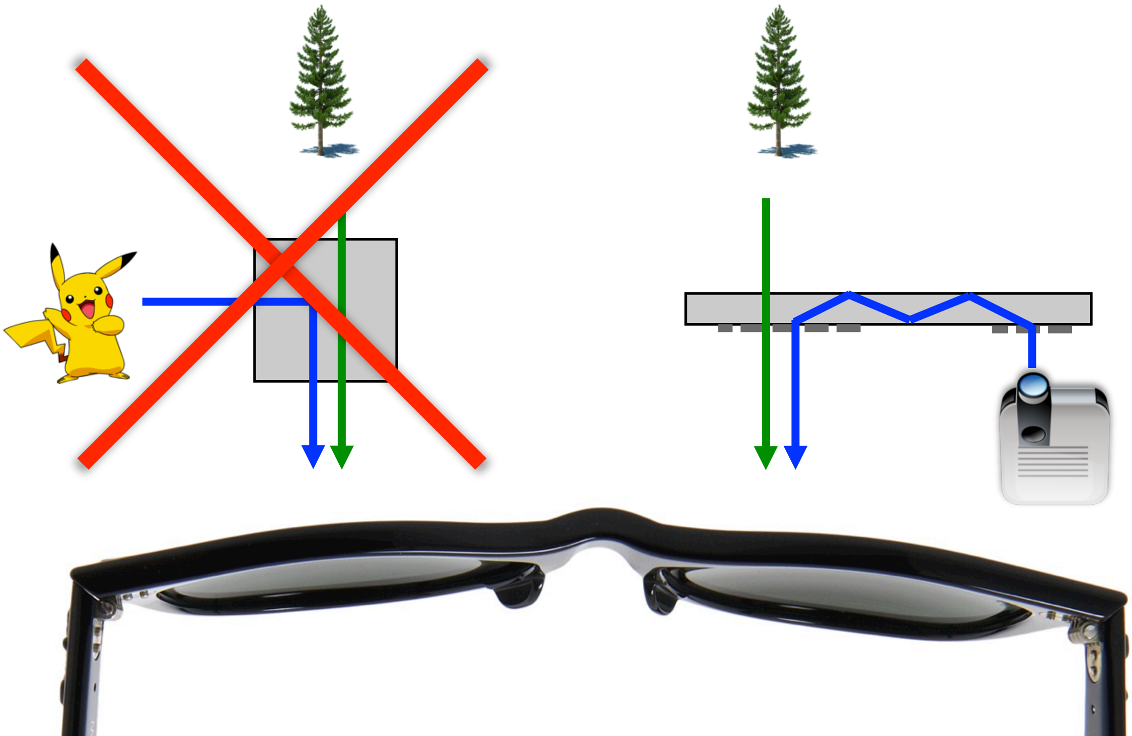


Photonics Challenges for Getting Here

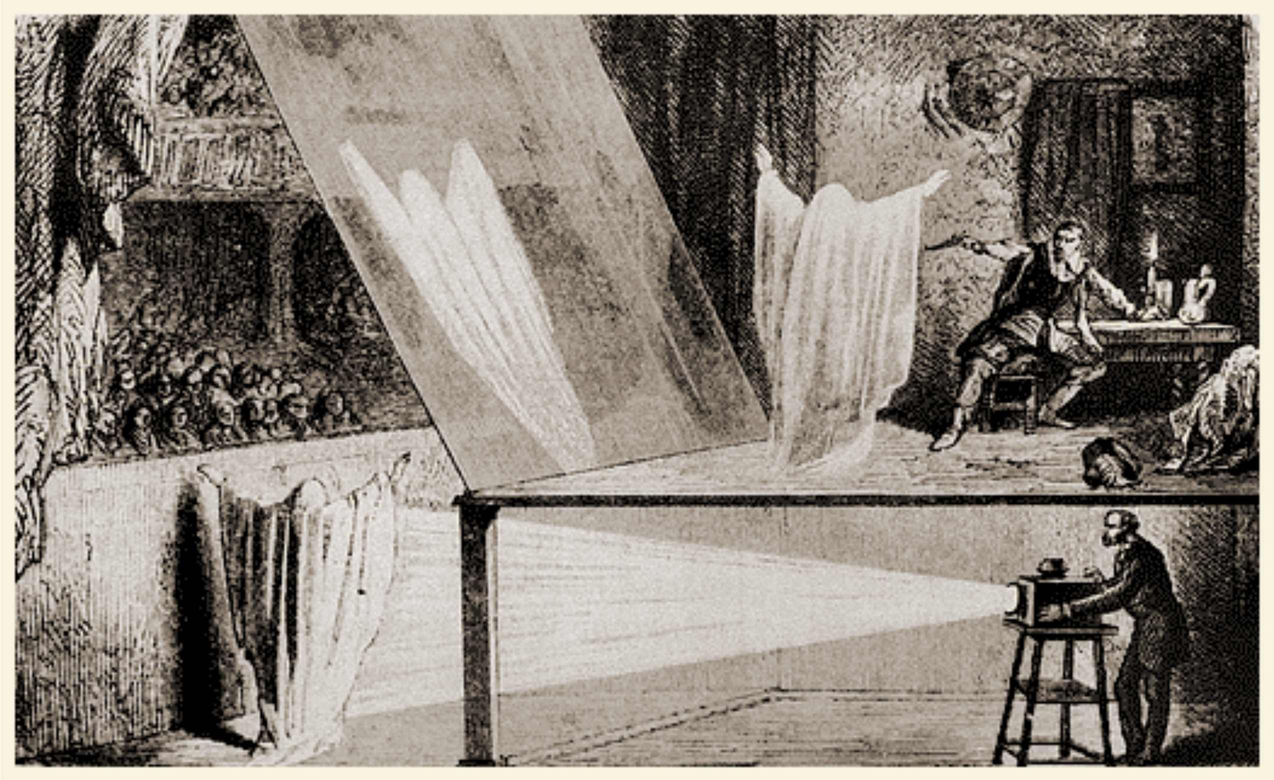
Thin Beam Combiner?



Thin Beam Combiner!

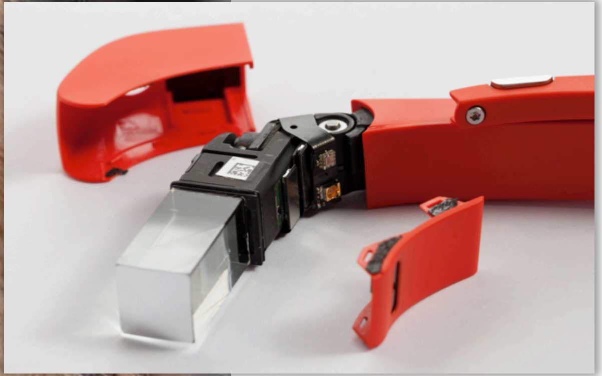


Pepper’s Ghost 1862

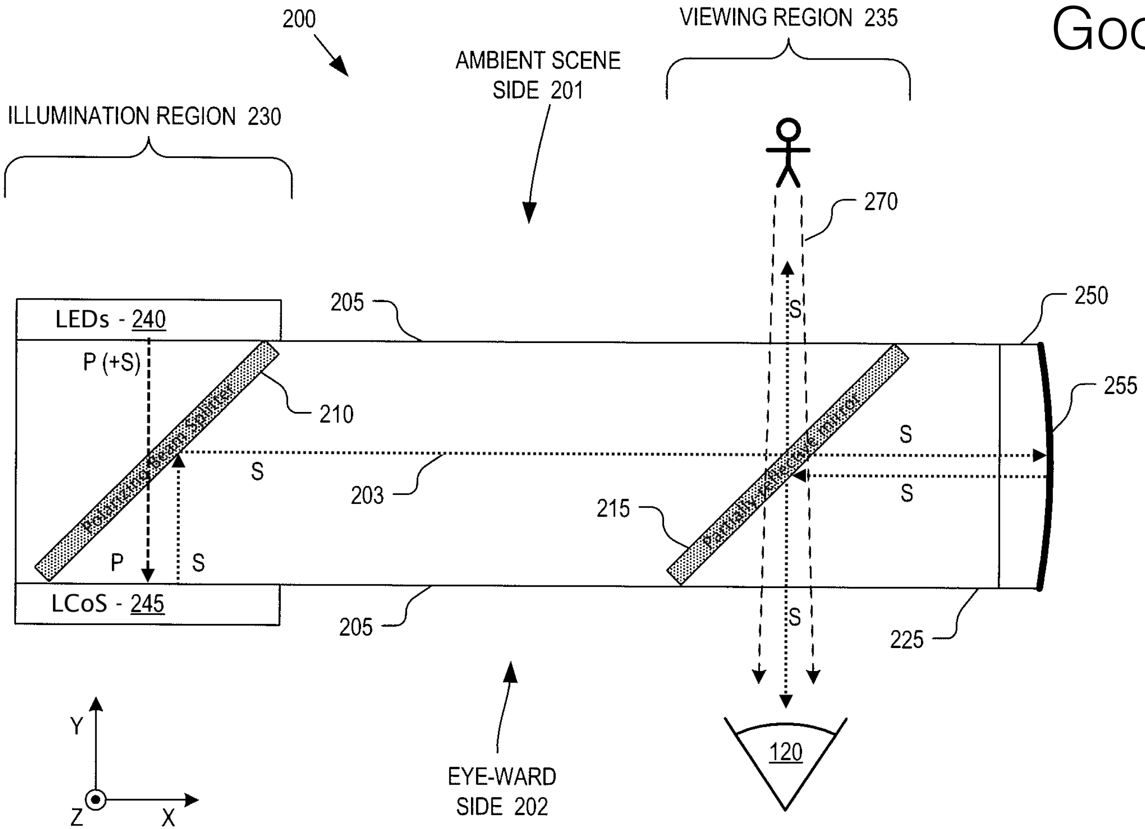


Case Studies

Google Glass



Google Glass



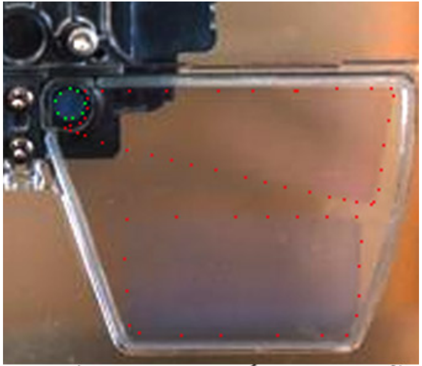
Meta 2

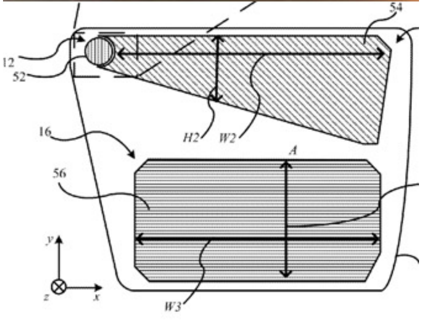
- larger field of view (90 deg) than Glass
- also larger device form factor

Microsoft HoloLens

Microsoft HoloLens

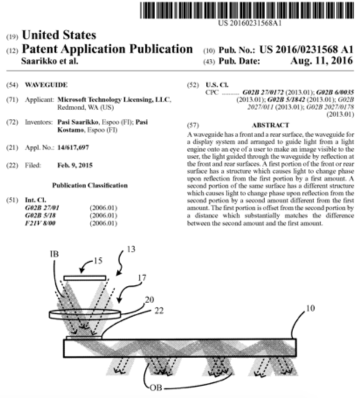
- diffraction grating
- small FOV (30x17), but very good image quality





US 2016/0231568

Fig. 3B



US 20160231568A1

(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

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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)

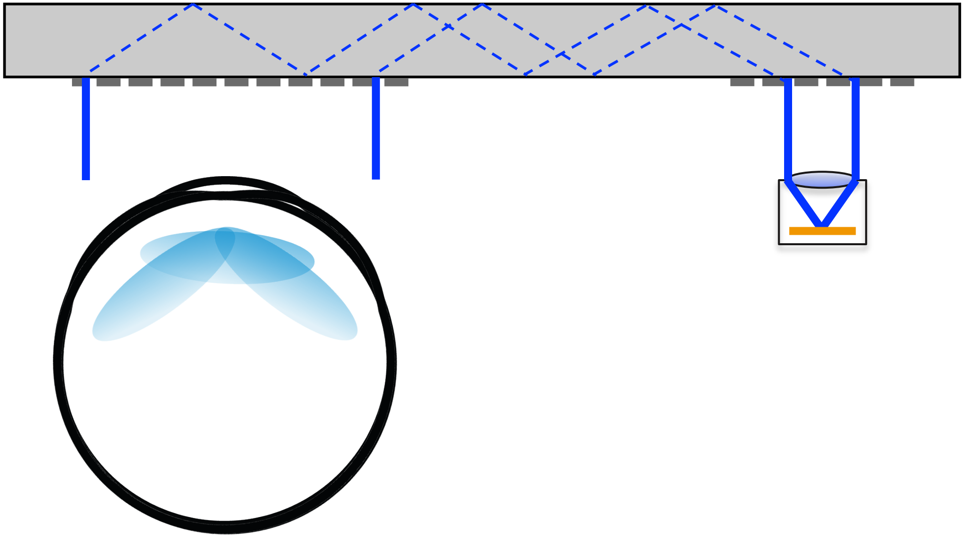
(57) ABSTRACT

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.

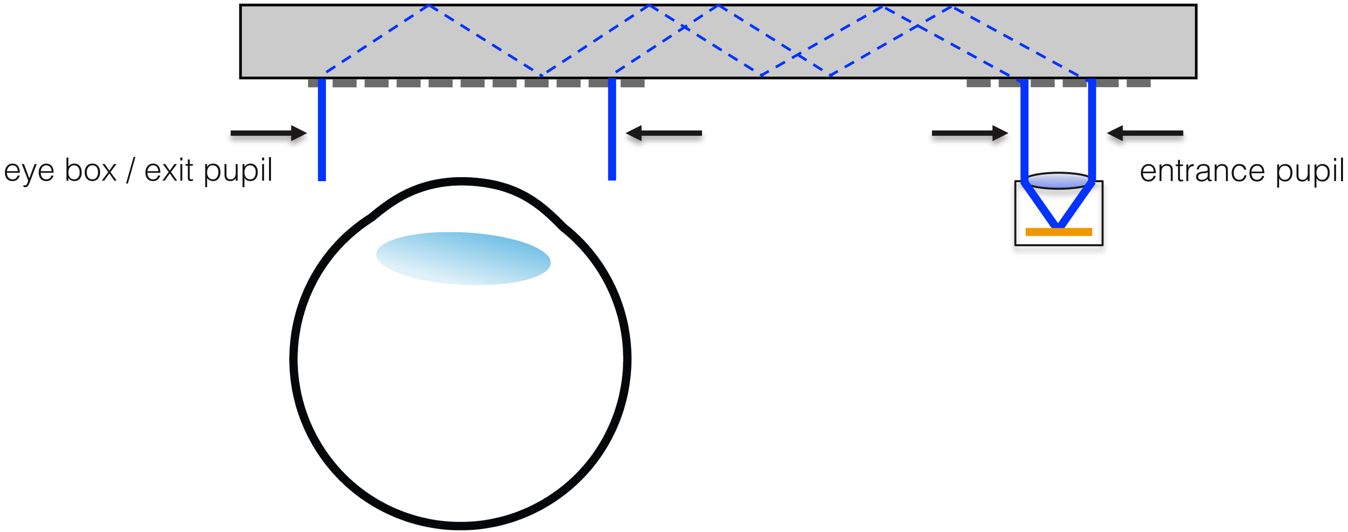
Zeiss Smart Optics

- great device form factor
- polycarbonate light guide – easy to manufacture and robust
- smaller field of view (17 deg)

Challenges: Eye Box vs Field of View

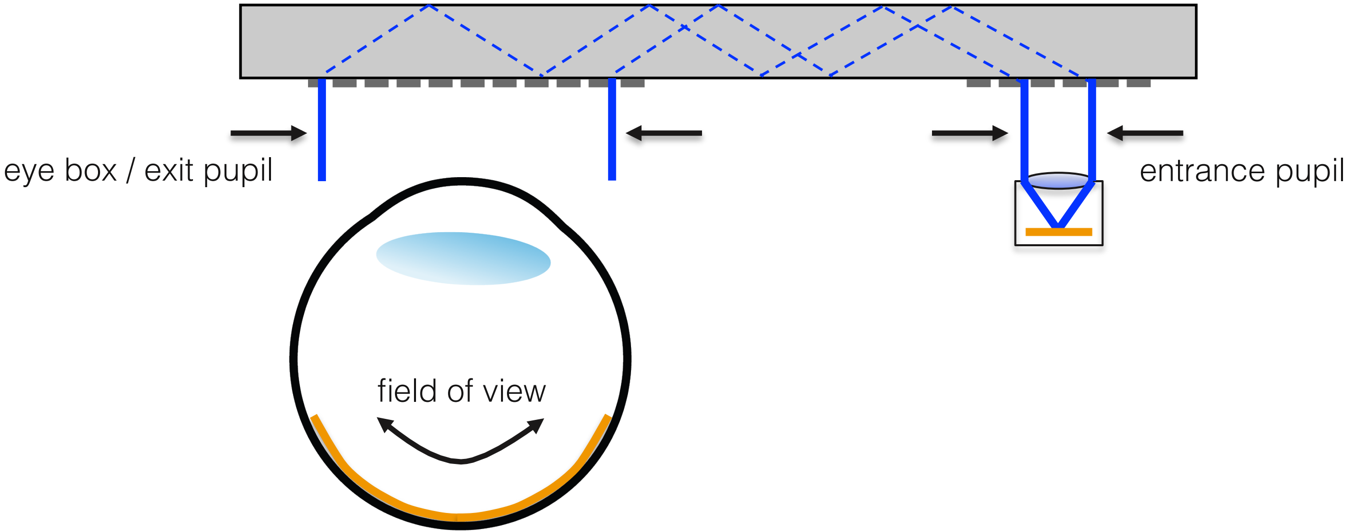


Challenges: Eye Box vs Field of View



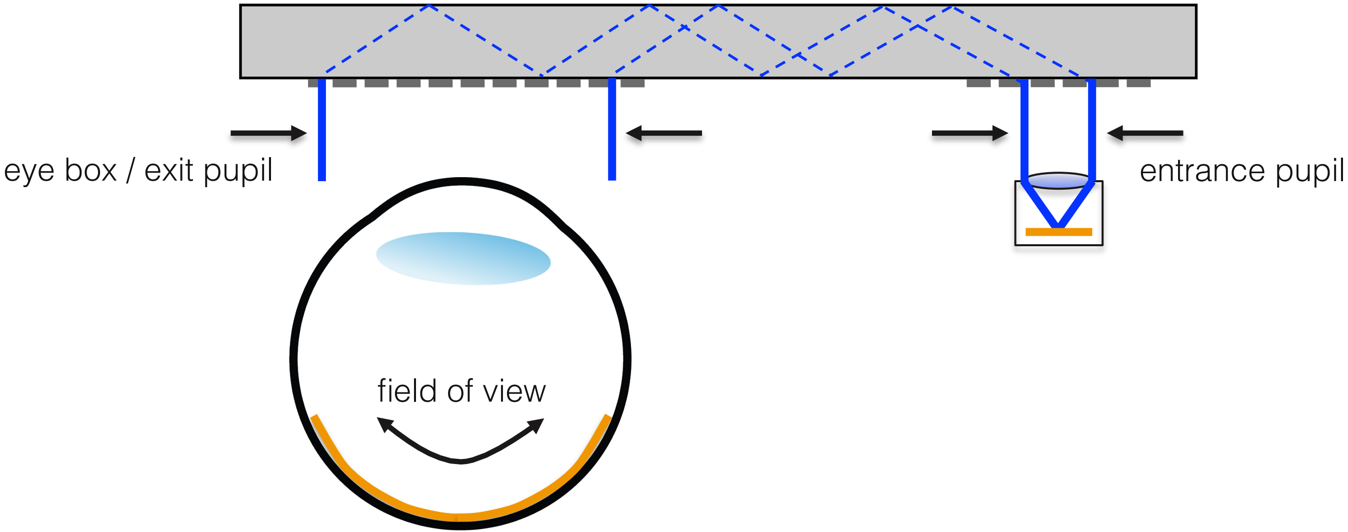
- need small entrance pupil (small device) and large exit pupil (large eye box) - pupil needs to be magnified

Challenges: Eye Box vs Field of View

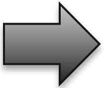


- need small display (small device) but large field of view – image needs to be magnified

Challenges: Eye Box vs Field of View

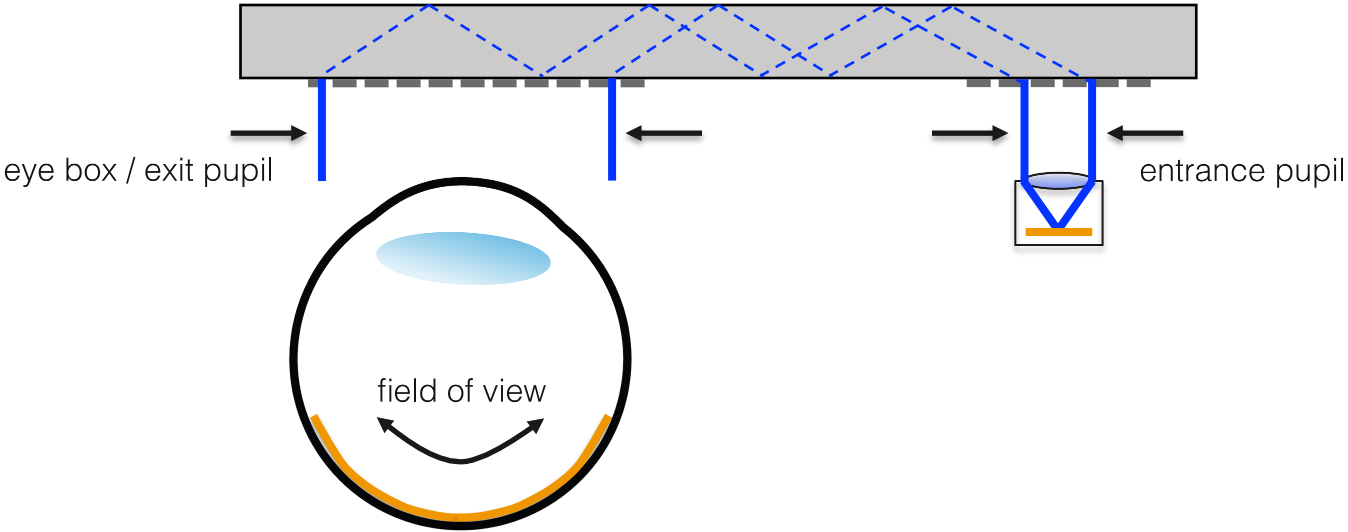


- pupil needs to be magnified
- image needs to be magnified



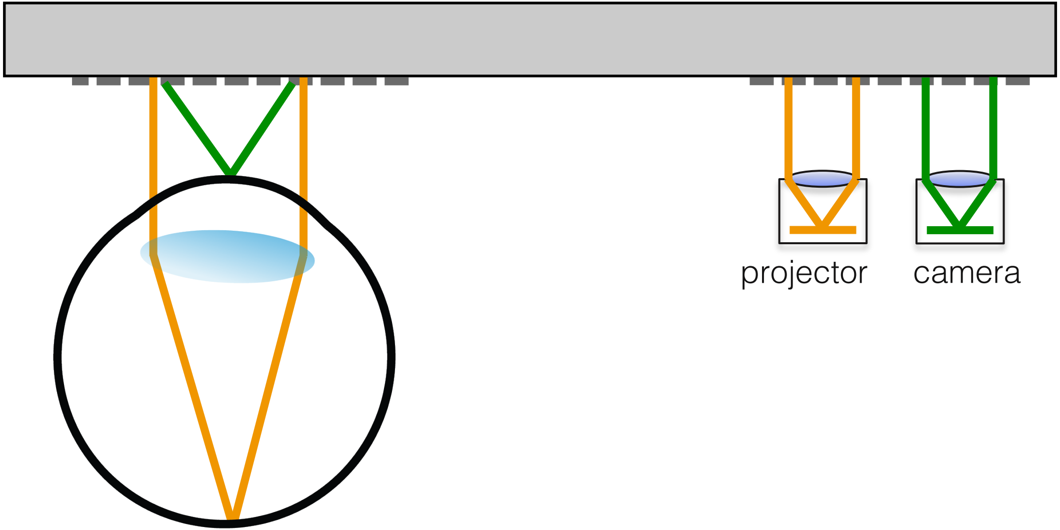
can't get both at the same time – etendue!

Challenges: Eye Box vs Field of View



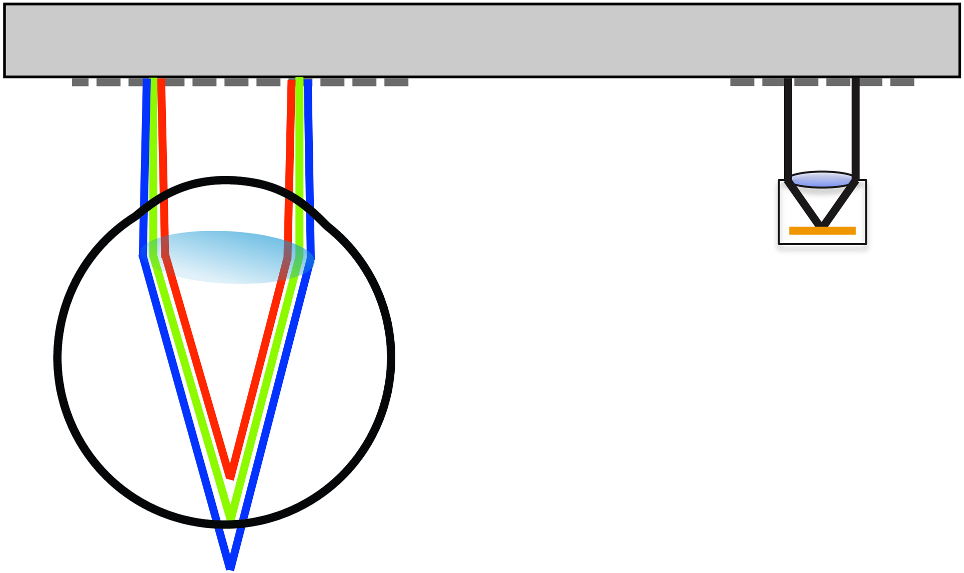
- possible solutions: exit pupil replication (loss of light), live with small FOV (not great), dynamically steer eye box (mechanically difficult), ..

Challenges: Eyetracking



- need eye tracking for correct calibration of display & world
- camera and projector need different optical paths! (no solution so far)

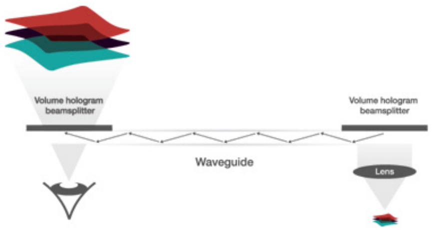
Challenges: Chromatic Aberrations



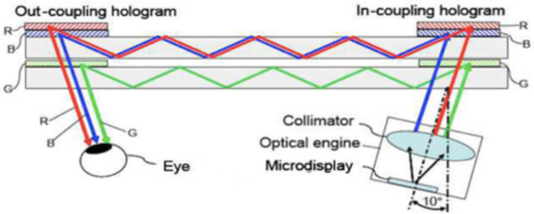
- thin grating couplers create chromatic aberrations

Challenges: Chromatic Aberrations

volume holographic couplers,
e.g. TruLife Optics



stacked waveguides

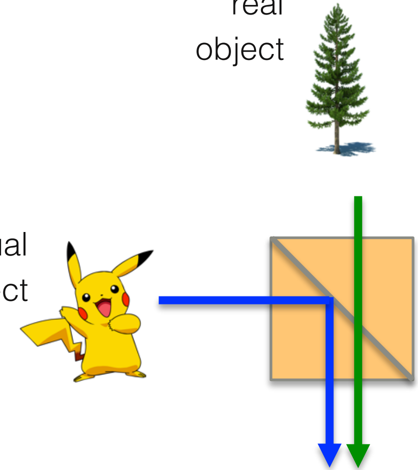


- all solutions have their own problems: ease of manufacturing, yield, robustness, cost, …

Occlusions

real object

virtual object



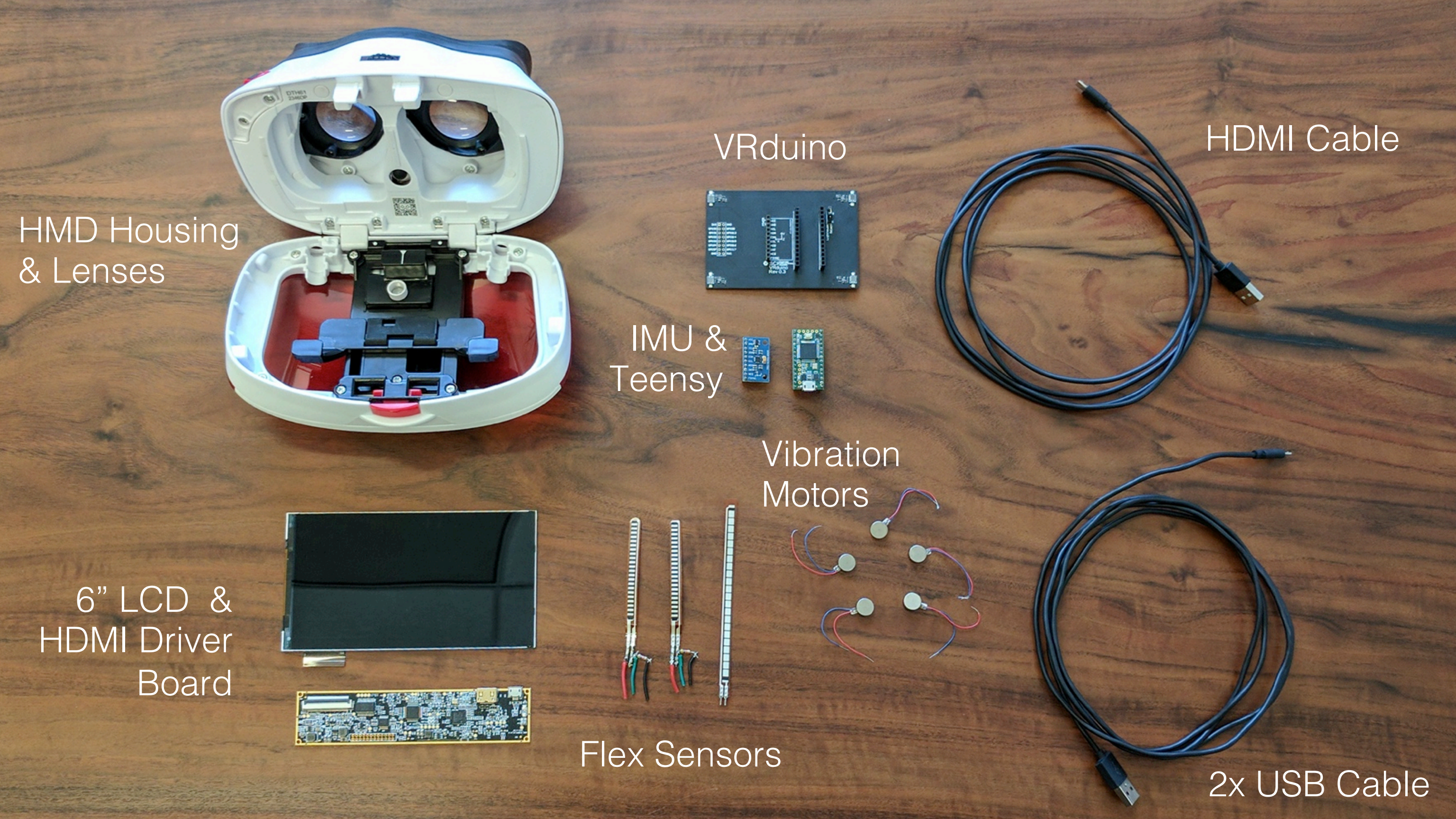
Case 1:
virtual in front of real

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

Case 2:
real in front of virtual

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

Stanford EE 267

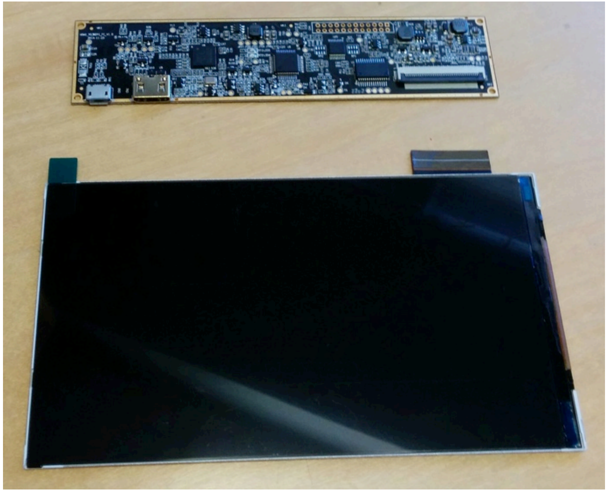


HMD Housing
& Lenses
VRduino
IMU &
Teensy
HDMI Cable
Vibration
Motors
6" LCD &
HDMI Driver
Board
Flex Sensors
2x USB Cable

HMD Housing and Lenses

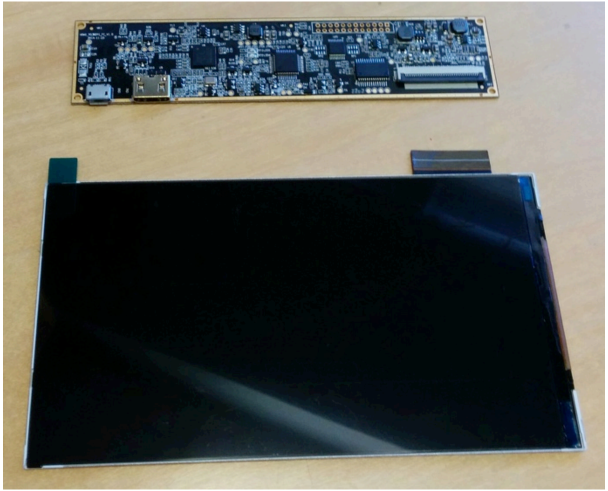
- View-Master VR Starter Kit ($15-20) or Deluxe VR Viewer ($23)
    - implements Google Cardboard 1.0/2.0
    - very durable – protect flimsy LCDs
    - may need to drill additional holes

Display



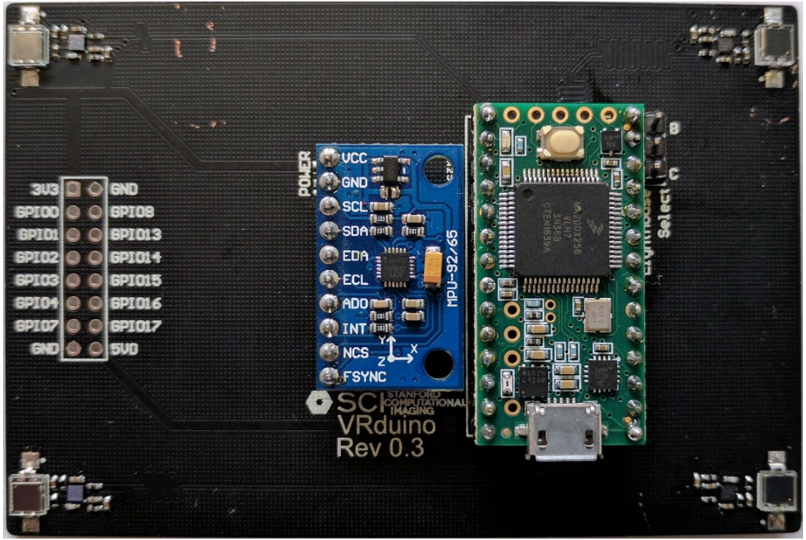
- Topfoison LCDs:
  - 1080p - $90
  - 1440p (2K) - $100
- HDMI driver boards included
- no audio jack! doesn’t fit in housing
- super easy to use as external monitor on desktop or laptop

Display



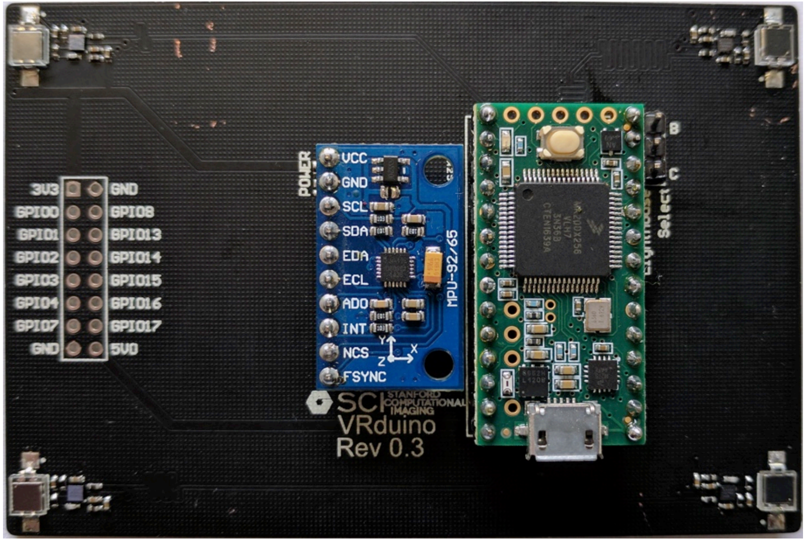
- same LCD you'll find in many smartphones
- reasonably robust (only broke a few)
- ideally use OLEDs, but haven't found any low-cost ones similar to these LCDs

VRduino



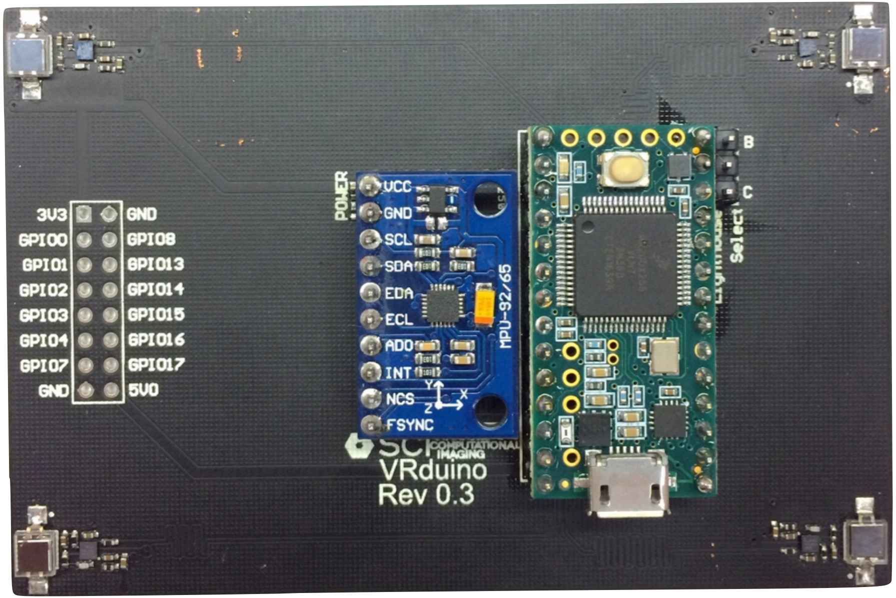
- Arduino-based open source platform for:
  - orientation tracking
  - positional tracking
  - interfacing with other IO devices
- custom-design for EE 267 by Keenan Molner
- all HW-related files on course website

VRduino

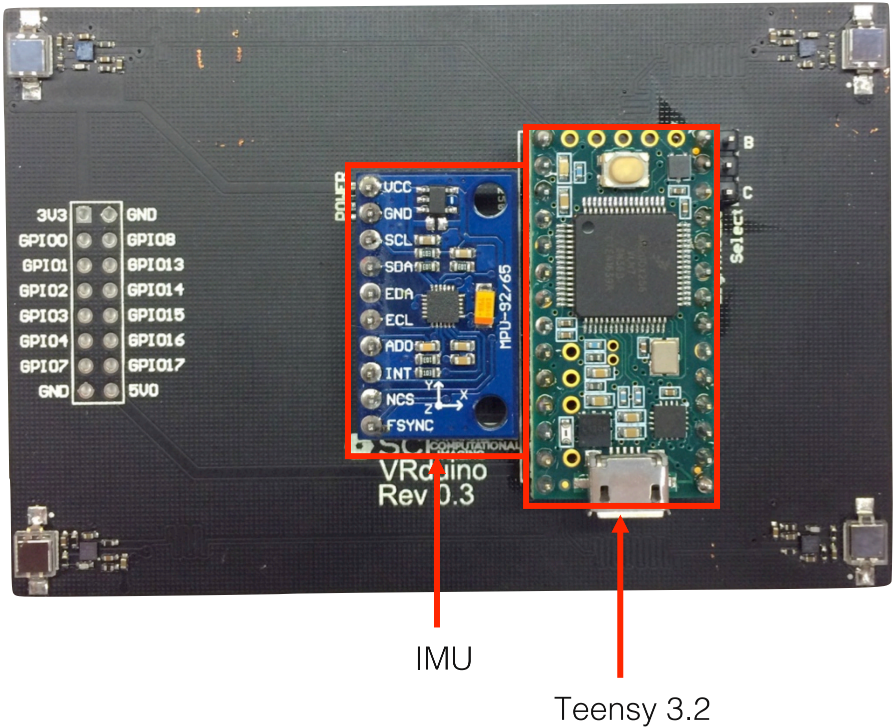


- Teensy 3.2 microcontroller (48 MHz, $20) for all processing & IO
- InvenSense 9250 IMU (9-DOF, $6) for orientation tracking
- Triad photodiodes & precondition circuit ($1) for position tracking with HTC Lighthouse

VRduino

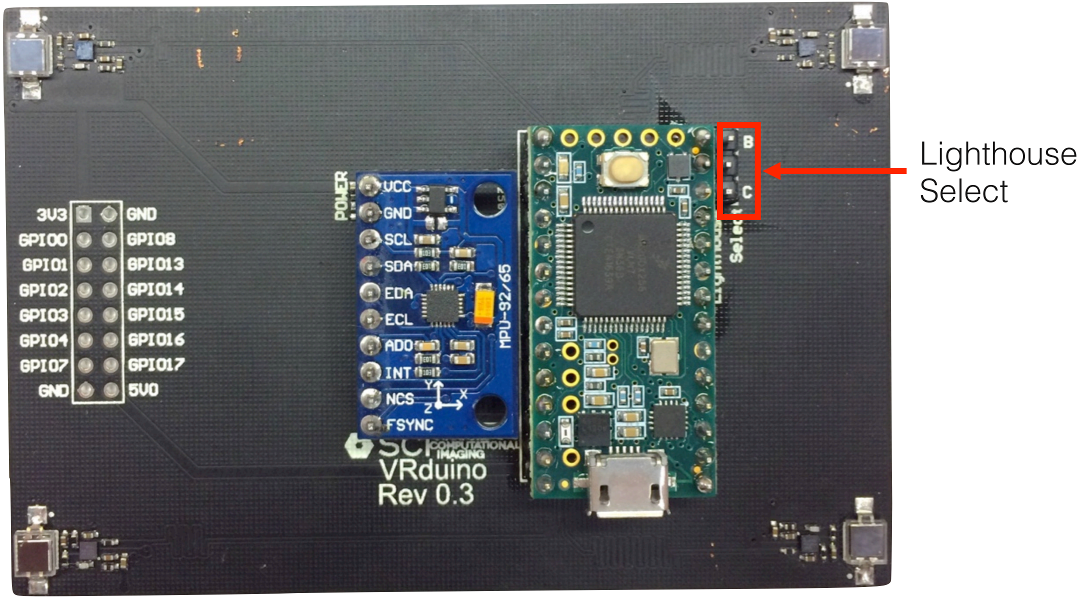

3V3
GND
GPIO0
GPIO8
GPIO1
GPIO13
GPIO2
GPIO14
GPIO3
GPIO15
GPIO4
GPIO16
GPIO7
GPIO17
GND
5V0
POWER
VCC
GND
SCL
SDA
EDA
ECL
ADO
INT
NCS
FSYNC
MPU-92/65
B
C
Select
VRduino
Rev 0.3

VRduino



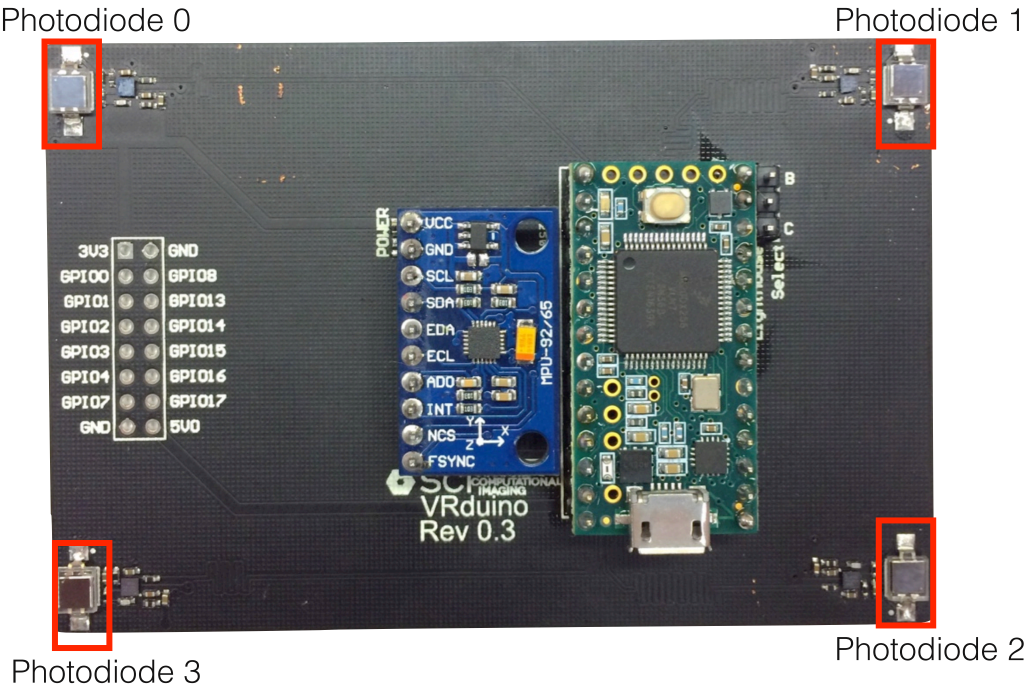
3V3
GND
GPIO0
GPIO8
GPIO1
GPIO13
GPIO2
GPIO14
GPIO3
GPIO15
GPIO4
GPIO16
GPIO7
GPIO17
GND
5V0
VCC
GND
SCL
SDA
EDA
ECL
ADD
INT
NCS
FSYNC
MPU-92/65
B
C
Select
VRduino
Rev 0.3
IMU
Teensy 3.2

VRduino



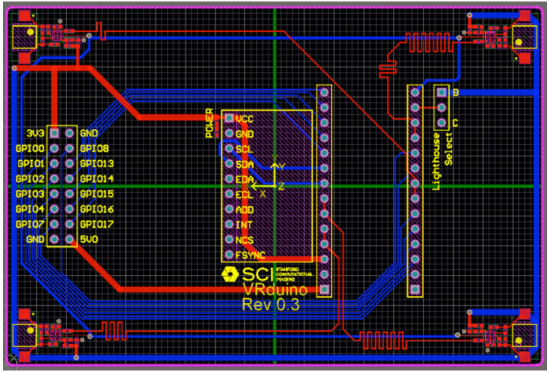
3V3
GND
GPIO0
GPIO8
GPIO1
GPIO13
GPIO2
GPIO14
GPIO3
GPIO15
GPIO4
GPIO16
GPIO7
GPIO17
GND
5V0
POWER
VCC
GND
SCL
SDA
EDA
ECL
ADD
INT
NCS
FSYNC
MPU-92/65
B
C
VRduino
Rev 0.3
Lighthouse
Select

VRduino



Photodiode 0
Photodiode 1
Photodiode 2
Photodiode 3
3V3
GND
GPIO0
GPIO8
GPIO1
GPIO13
GPIO2
GPIO14
GPIO3
GPIO15
GPIO4
GPIO16
GPIO7
GPIO17
GND
5V0
POWER
VCC
GND
SCL
SDA
EDA
ECL
ADD
INT
NCS
FSYNC
MPU-92/65
B
C
Select
SCI COMPUTATIONAL IMAGING
VRduino
Rev 0.3

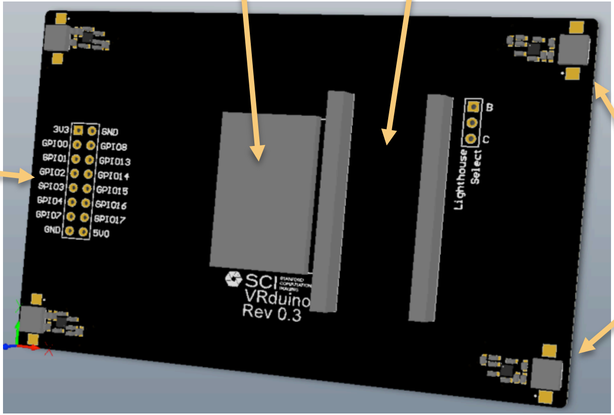
About EE 267 – VRduino



Teensy 3.2

IMU

other GPIO pins

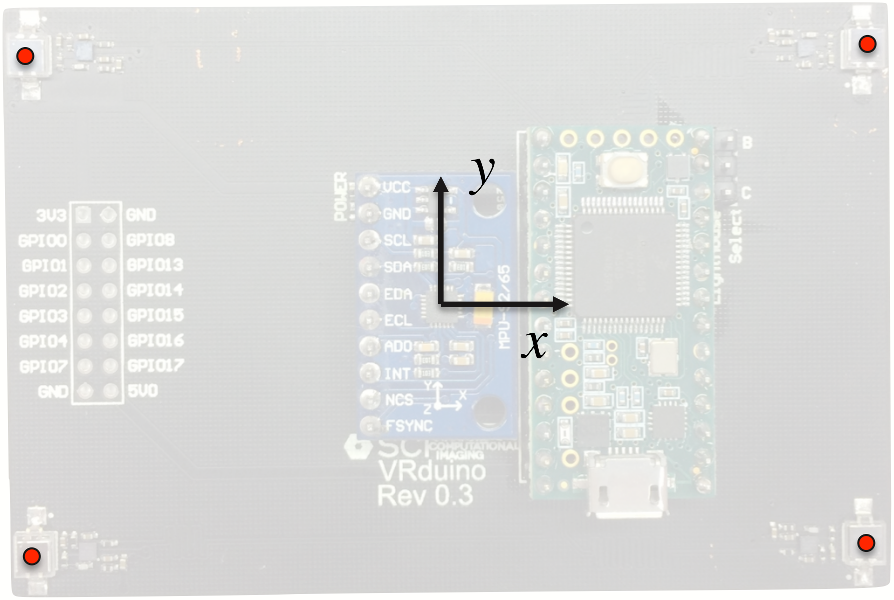


4 photodiodes

VRduino

x=-42mm, y=25mm

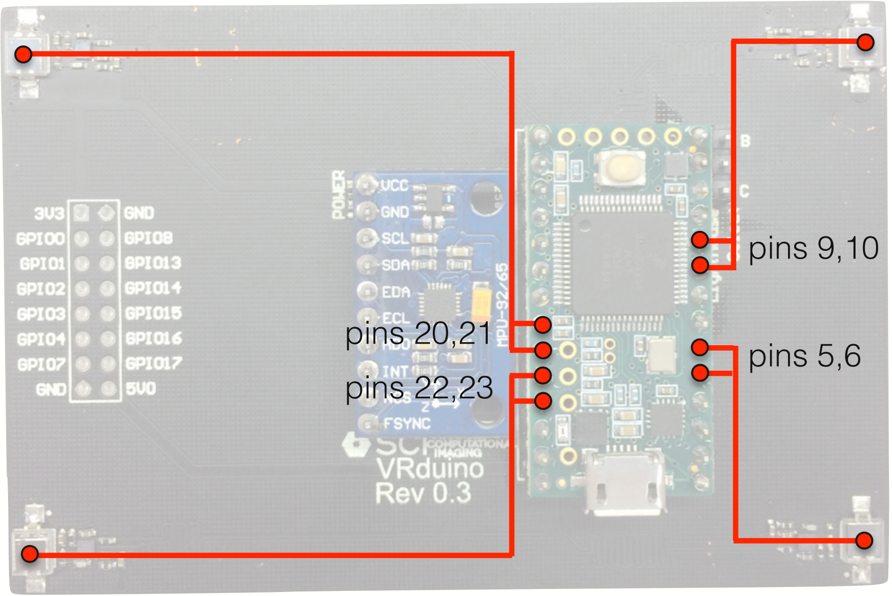
x=42mm, y=25mm



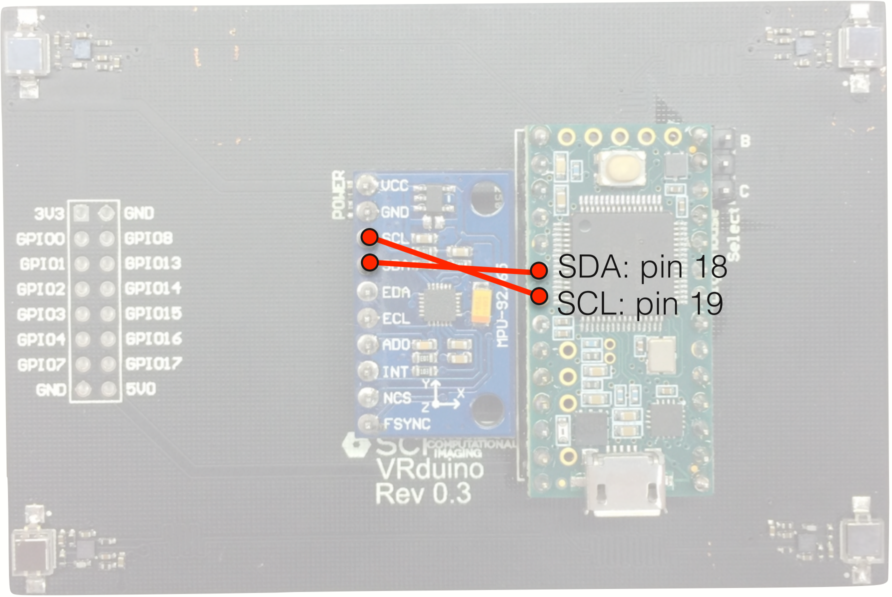
x=-42mm, y=-25mm

x=42mm, y=-25mm

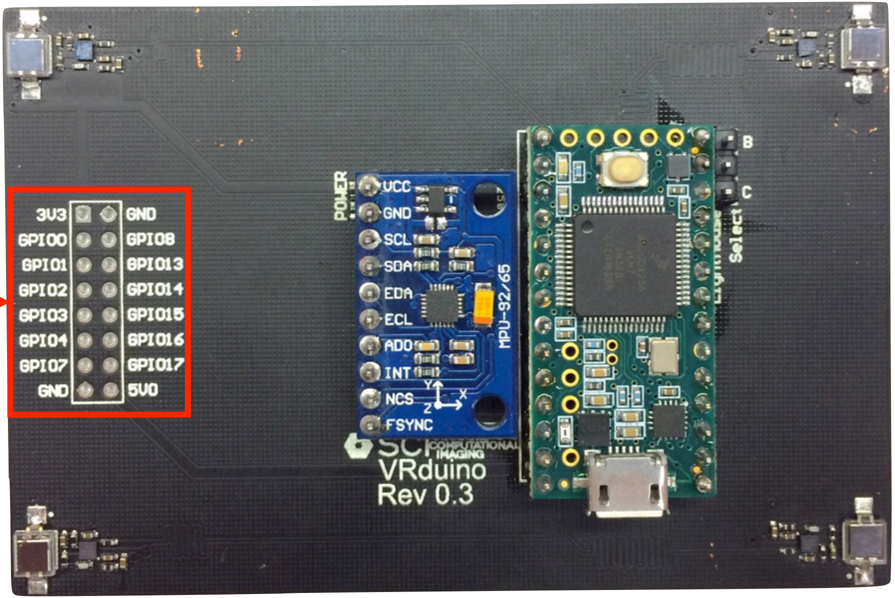
VRduino


pins 9,10
pins 20,21
pins 22,23
pins 5,6
3V3
GND
GPIO0
GPIO8
GPIO1
GPIO13
GPIO2
GPIO14
GPIO3
GPIO15
GPIO4
GPIO16
GPIO7
GPIO17
GND
5V0
POWER
VCC
GND
SCL
SDA
EDA
ECL
INT
FSYNC
MPU-92/65
B
C
VRduino
Rev 0.3

VRduino


SDA: pin 18
SCL: pin 19
3V3
GND
GPIO0
GPIO8
GPIO1
GPIO13
GPIO2
GPIO14
GPIO3
GPIO15
GPIO4
GPIO16
GPIO7
GPIO17
GND
5V0
POWER
VCC
GND
SCL
EDA
ECL
ADO
INT
NCS
FSYNC
VRduino
Rev 0.3

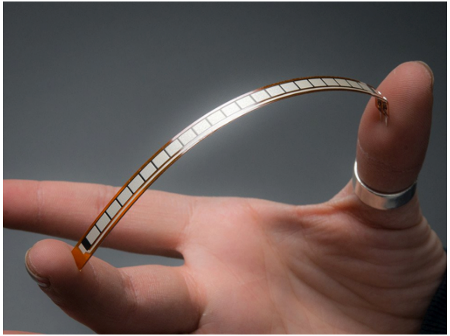
VRduino

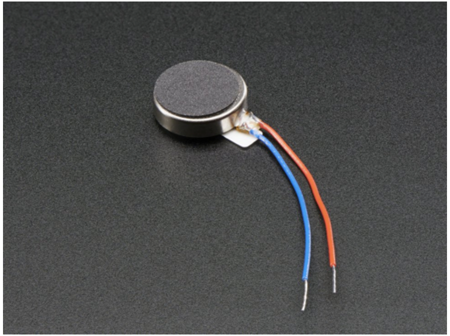


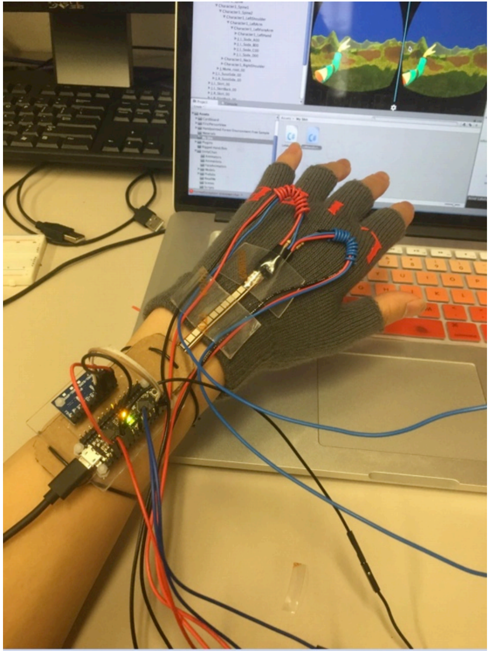
Pin Breakout

Student-built Input Devices

- data gloves with flex sensors
- different types of controllers with tactile feedback via vibration motors
- all connected to VRduino GPIO pins







images from Adafruit.com

Acknowledgements

Near-eye Displays

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

Light field displays

- Doug Lanman (Oculus)
- Matt Hirsch (Lumii)
- Andrew Maimone (Oculus)
- Henry Fuchs (UNC)

Other

- Wolfgang Heidrich (UBC/KAUST)
- Ramesh Raskar (MIT/Facebook)
- Ed Boyden (MIT)
- Joseph Ford (UCSD)
- Karl Deisseroth (Stanford)

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Computational Imaging Group
Stanford University

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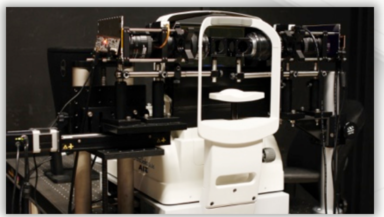
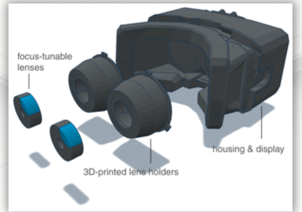
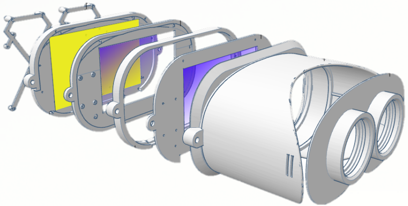
www.computationalimaging.org







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