IEEE VR 2018
REUTLINGEN

Cutting-edge VR/AR Display Technologies

(Gaze-, Accommodation-, Motion-aware and HDR-enabled)

George-Alex Koulieris

Kaan Akşit

Christian Richardt

Rafał Mantiuk

Katerina Mania

Inria GraphDeco

NVIDIA

University of Bath

University of Cambridge

Technical Univ. of Crete

Tutorial at a glance

- Understand current VR/AR display challenges
- Learn how challenges relate to visual perception
- What can we do about them?
- Discover the state-of-the-art in relevant research

George-Alex Koulieris

Speakers

- Kaan Akşit, NVIDIA, USA
- Katerina Mania, Technical University of Crete, Greece
- Rafał Mantiuk, University of Cambridge, UK
- Christian Richardt, University of Bath, UK
- George-Alex Koulieris, Inria, France

Schedule

- 9:00 – 9:30: Introduction
- 9:30 – 10:15: Multi-focal displays
- 10:30 - 11:00: Coffee break
- 11:00 – 11:50: Near-eye varifocal AR
- 12:00 - 14:00: Lunch
- 14:00 – 14:40: HDR-enabled displays
- 14:45 – 15:25: Gaze-aware displays
- 15:30 – 16:00: Coffee break
- 16:00 – 16:50: Motion-aware displays
- 17:00 – 17:20: Panel

Let’s get started

A Turing test for displays

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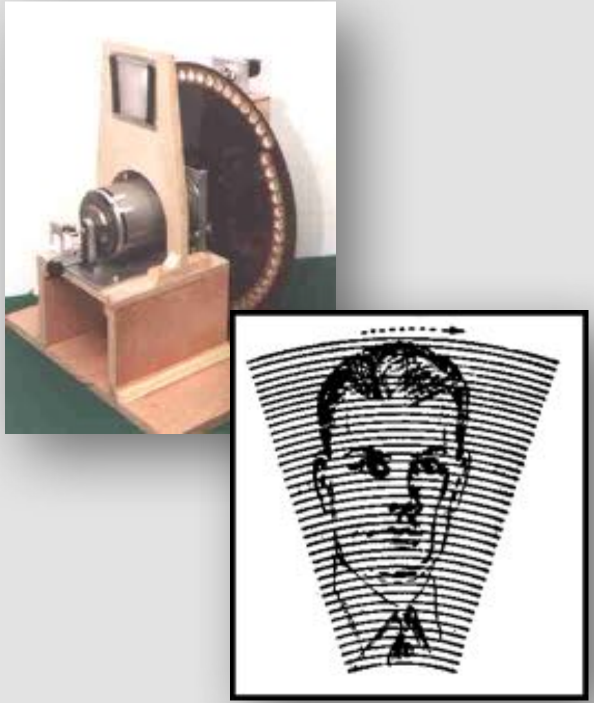
Displays

- Displays are virtual windows to remote scenes
- We have gone far from the Nipkow disk …



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Virtual, augmented, mixed reality displays

- Collectively, near-eye displays
- Immersion into virtual/augmented world
- Response to head motion
- Allows object manipulation/interaction

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VR/AR/MR applications

- **Education**
- **Communication**
- **Healthcare**
- **Entertainment**
- **Manufacturing**
- Aviation
- Business
- Design
- Gaming
- Marketing
- Shopping
- Sports
- Travel
- Therapy

Near-eye displays market explosion

- Top companies involved
- Market flooded with devices
- "*A billion people in virtual reality*"
  Mark Zuckerberg, 2017
- Research surge:
  SIGGRAPH, IEEE VR, ISMAR, …

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Before this becomes commonplace…

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Current display challenges

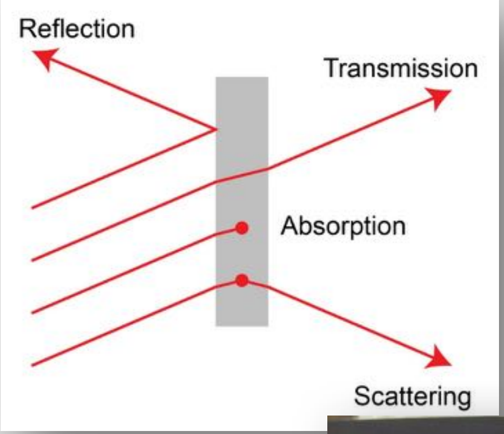
- Ergonomic / Comfort
- Visual Quality issues
- Perceptual
- Technical
- Interaction

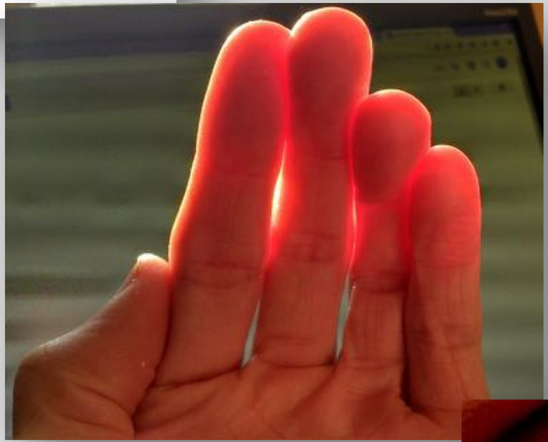
Exploiting knowledge from visual perception

- Display hardware and algorithms limited
- Produce different to natural light patterns
- Luckily, human visual system (HVS) limited
- Requirements restricted by HVS capabilities
- Visual perception as the optimizing function
- Achieve *perceptual effectiveness*
- Avoiding under-/over-engineering displays

But how do we take knowledge from visual perception into account?

Human vision





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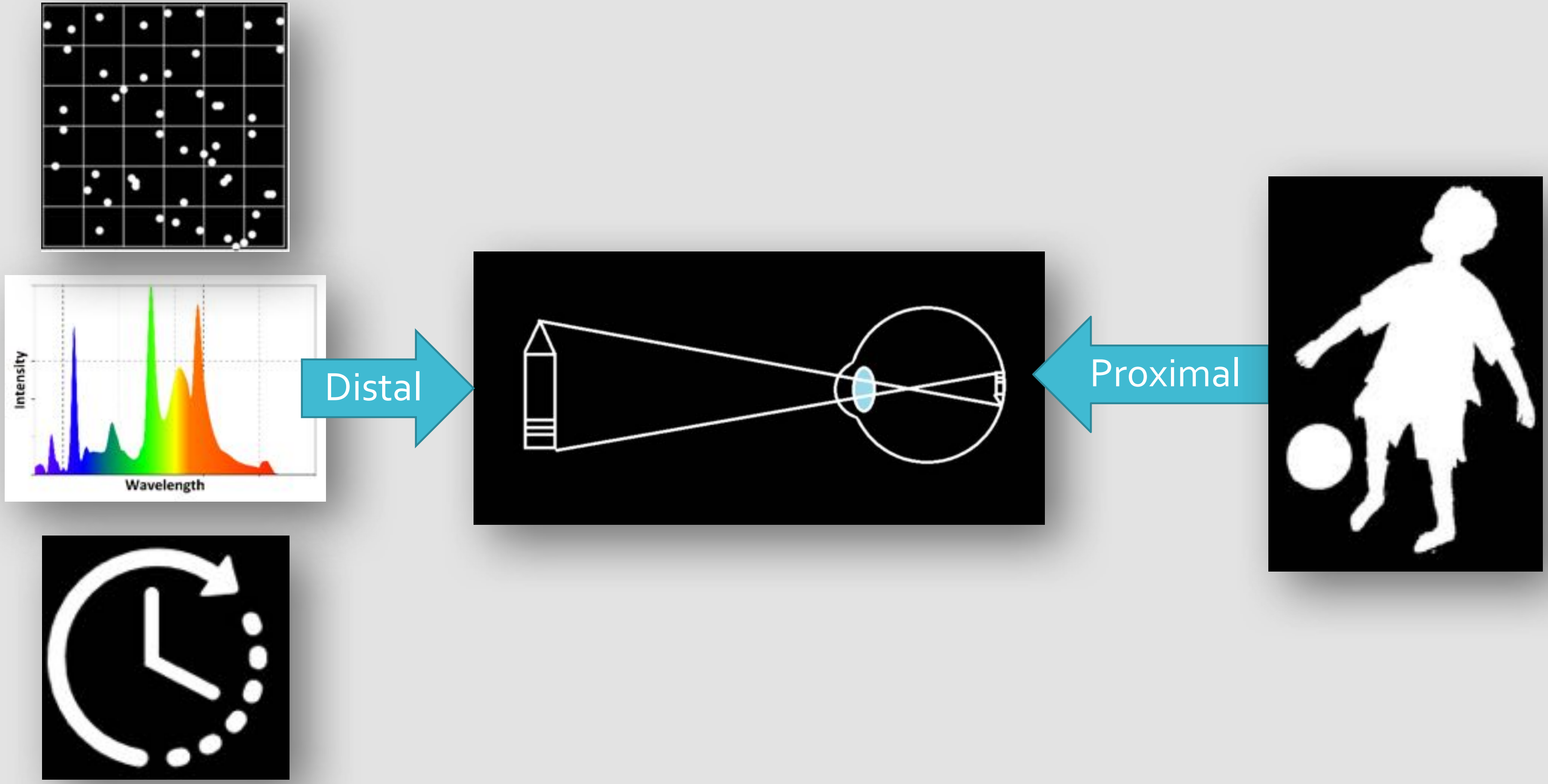
What visual perception does



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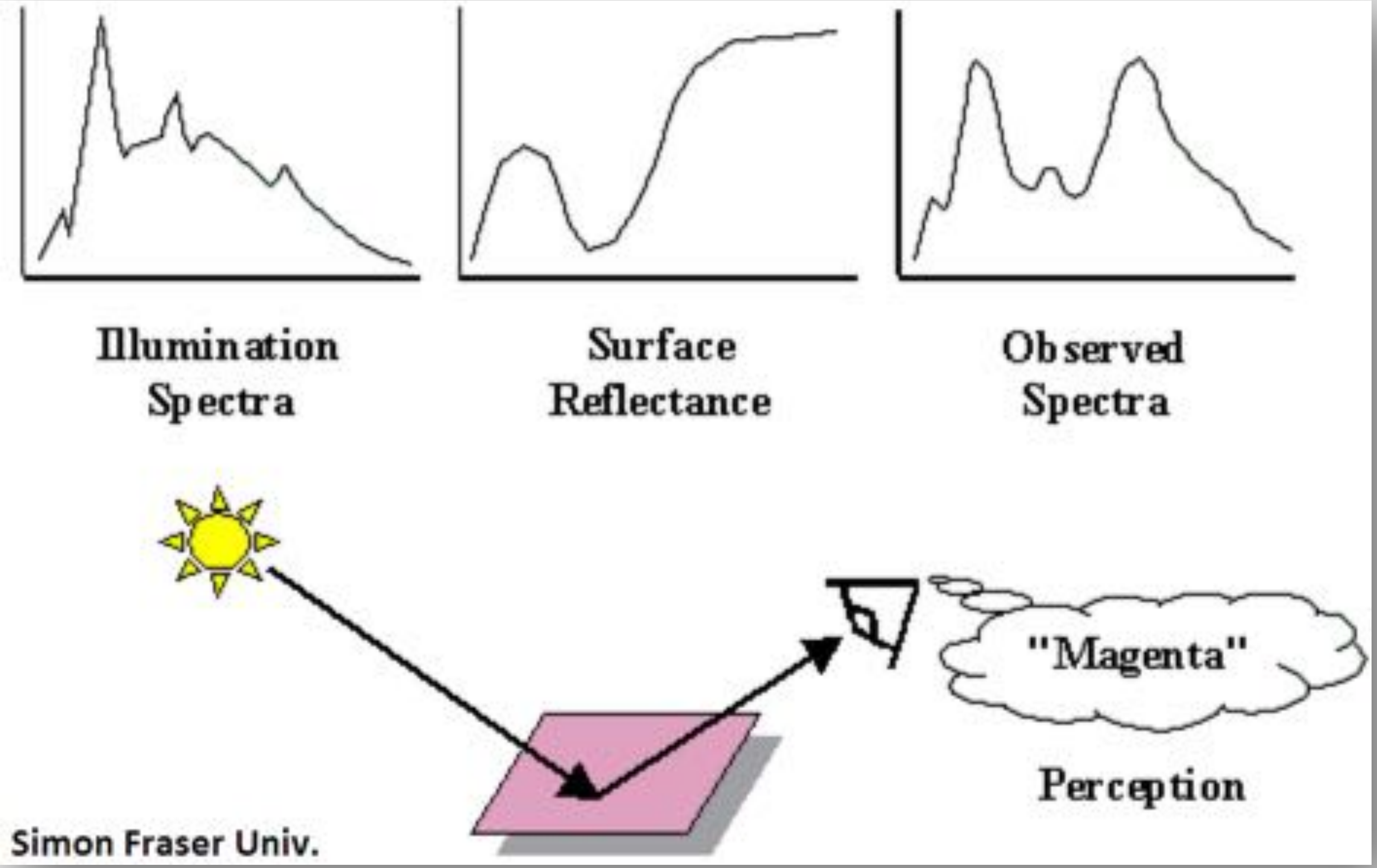
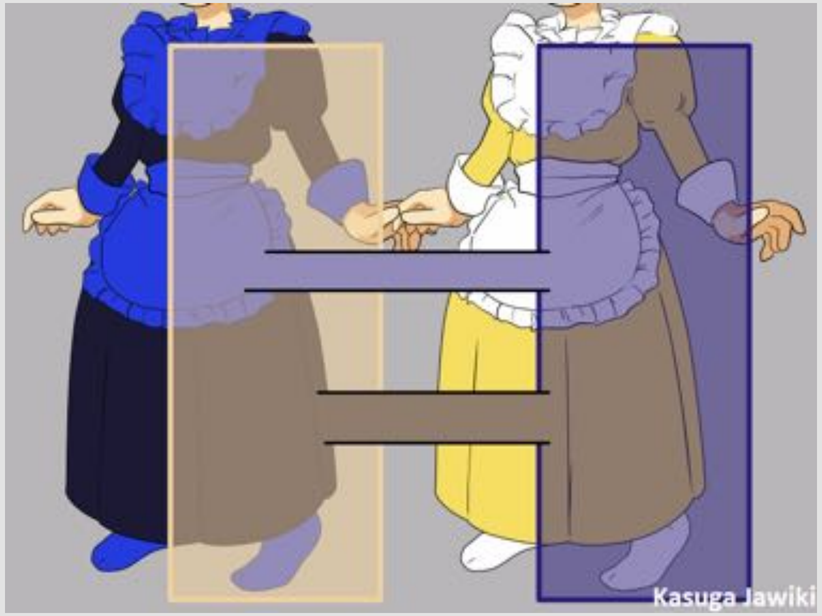
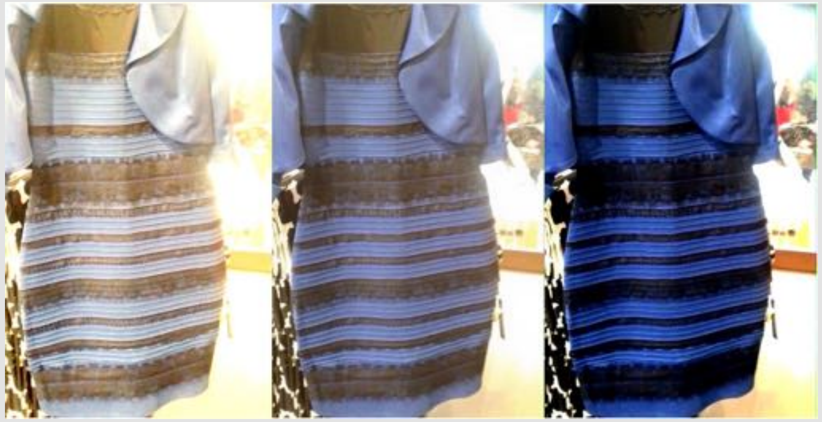
Proximal → Distal: A difficult, inverse problem



#thedress





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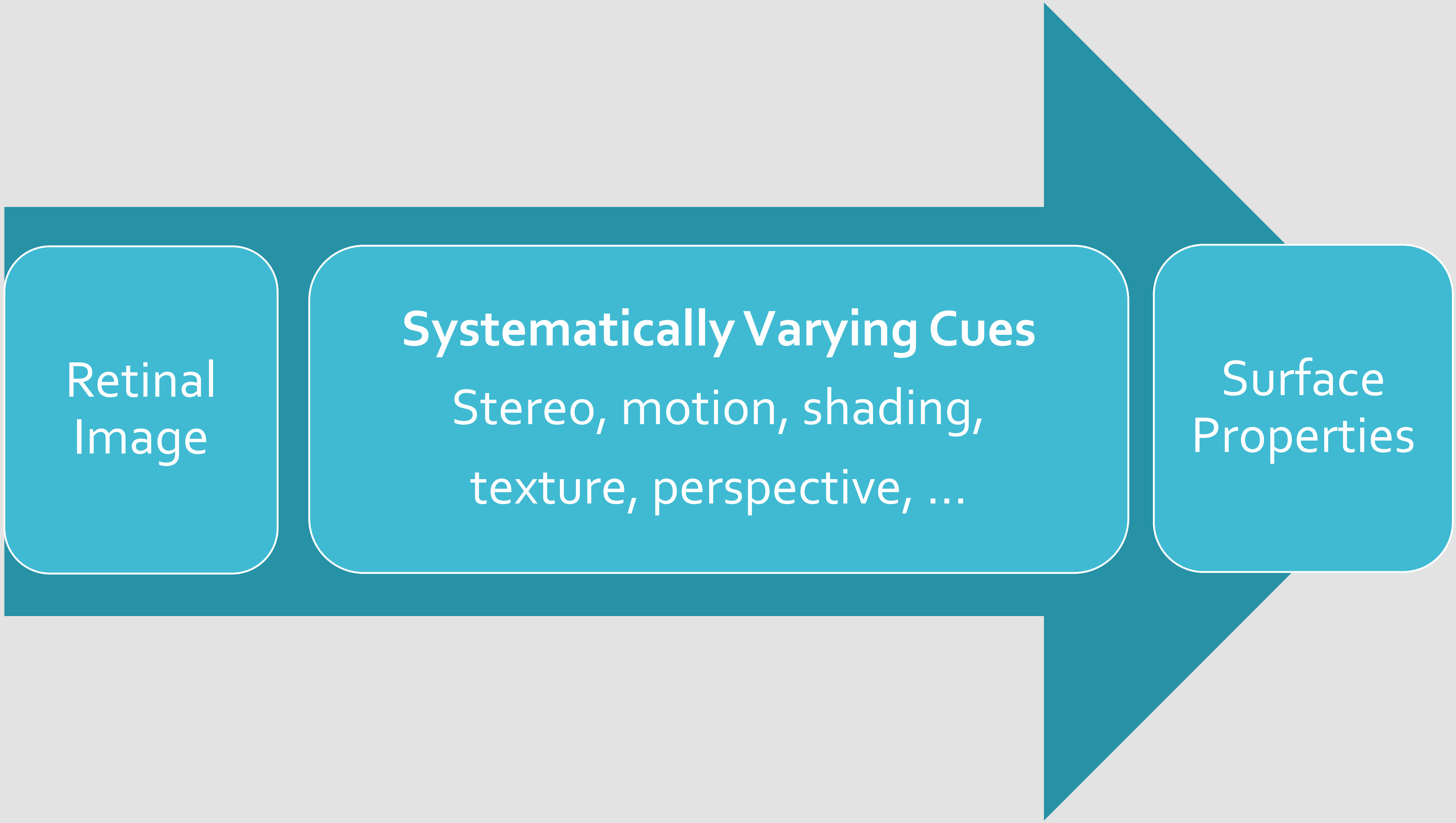
Visual perception and visual cues



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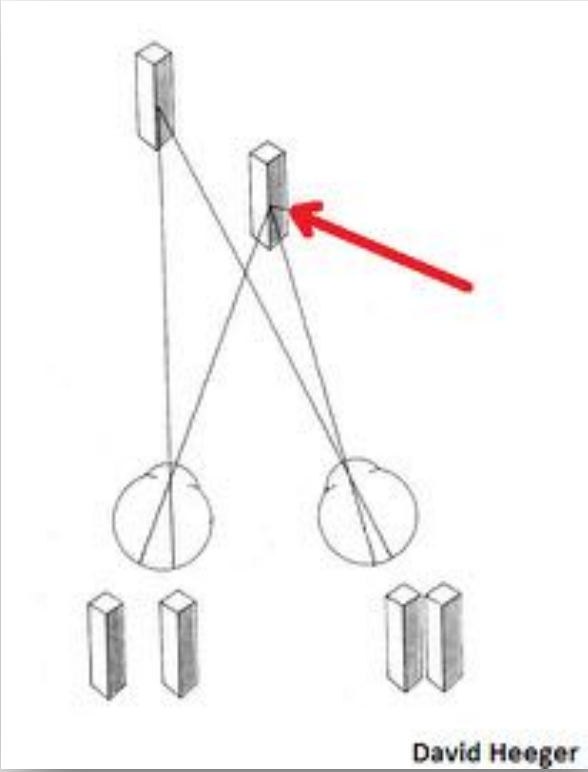
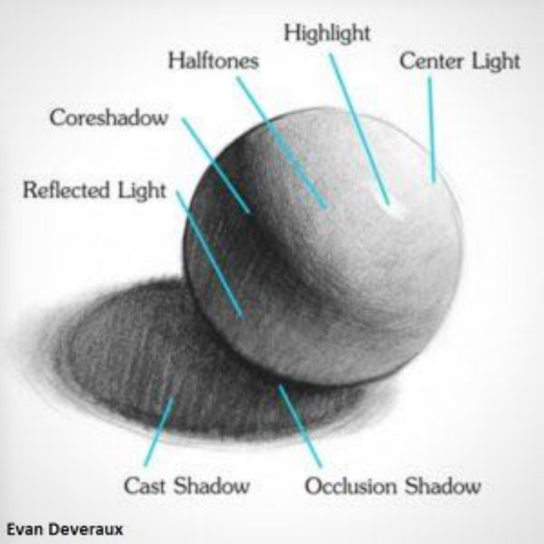
Examples of visual cues

- Ocular-motor cues
  - eye position, focus
- Binocular disparity cues
- Motion cues
  - world, viewer
- Pictorial cues (monocular)
  - familiar size
  - relative size
  - shading
  - texture gradients
  - occlusion
  - …





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Cue integration

- Cues expected to **co-vary** for same environmental properties
- Expected consistent information overlap

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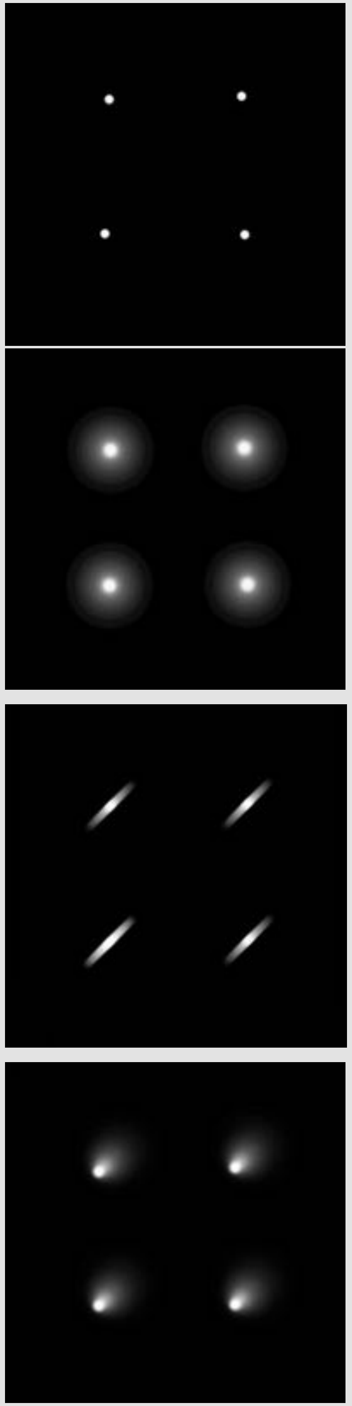
Cue conflicts

- Cues often conflicting due to
  - VS errors
  - incomplete information (e.g., displays)
  - incorrect assumptions about the natural environment



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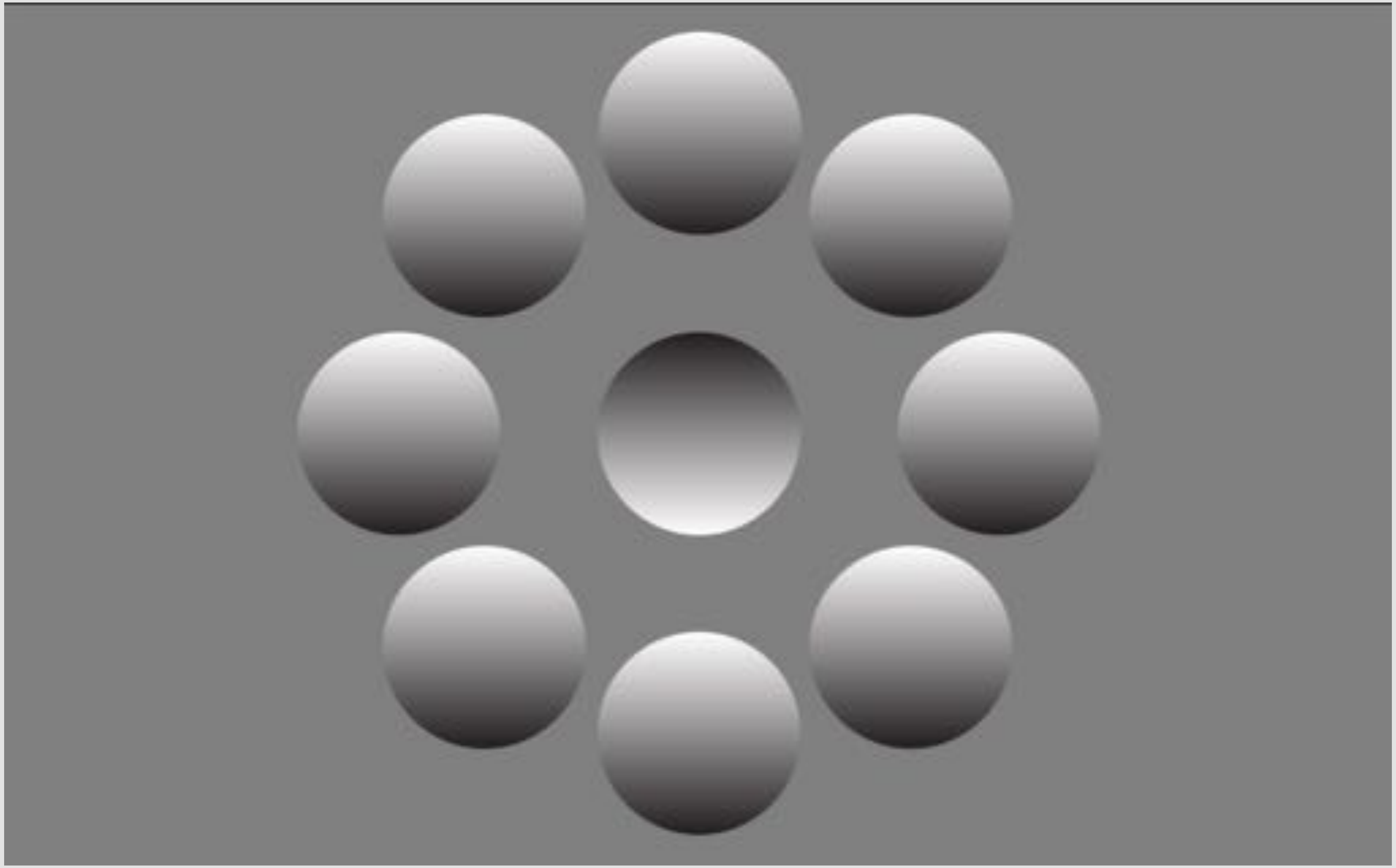
Fun fact: conflicting cues



How do we study visual perception?

Psychophysical methods of study (1)

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1. Show visual stimuli
2. Ask simple questions
3. Vary stimuli
4. GOTO 1

Psychophysical methods of study (2)

- N-A Forced choice tasks
- Method of adjustment
- Ascending/descending limits
- Staircase
- Constant stimuli

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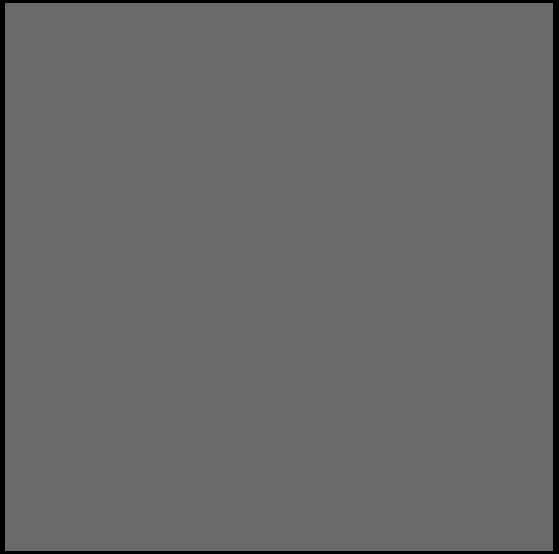
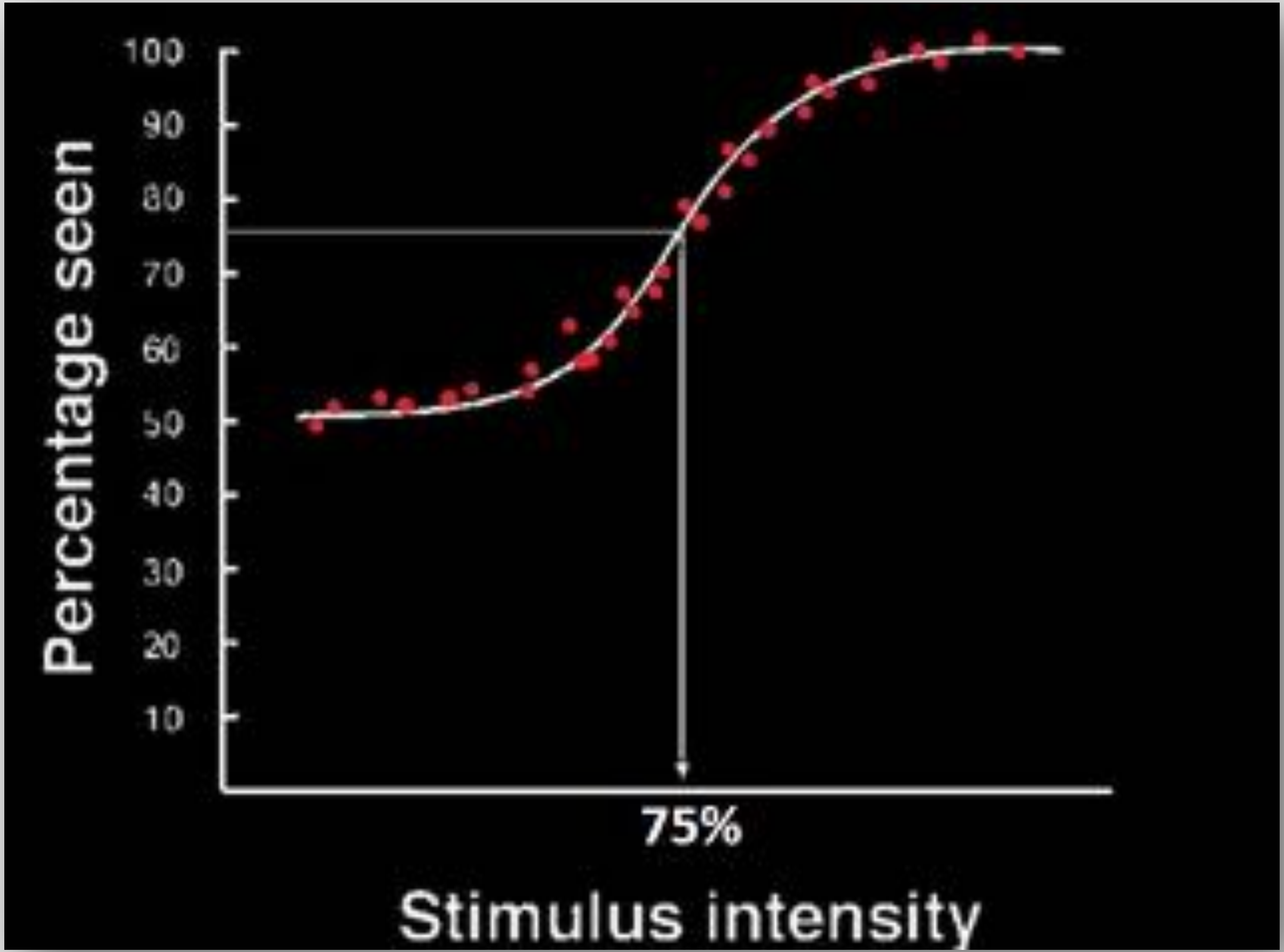
Example: luminance threshold detection



- 200ms patch
- PRESENT / ABSENT ?

Psychometric functions



75% is half-way between chance and perfect performance!

Course take-aways

Course take-aways (1)

Q: Why multifocal displays?

Q: Why varifocal AR?

A: Eyes evolved to focus on objects.

Kaan Akşit

George Alex Koulieris

Course take-aways (2)

Q: Why HDR-enabled displays?

A: Relates to the sensitivity of the eyes.

Rafał Mantiuk

UNIVERSITY OF CAMBRIDGE

George-Alex Koulieris

Course take-aways (3)

Q: Why gaze-aware displays?

A: Relates to the spatial acuity of the eyes.

Katerina Mania

Technical University of Crete

George-Alex Koulieris

Course take-aways (4)

Q: Why motion-aware displays?

A: Eyes attached on moving bodies.

Christian Richardt

UNIVERSITY OF BATH

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Summary

- Near-eye displays are beneficial to society
- Addressing challenges yields tremendous gains
- Near-eye displays a hot area for years to come
- Improving quality of experience in near-eye displays is an inter-disciplinary effort

- Questions so far?

Multi-focal Displays

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informatics mathematics

GraphDeco

GRAPHics and Design with hEterogeneous COntent

At a glance

- Part 1: basic optics, accommodation, VA conflict, discomfort, performance
- Part 2: multi-focal display technologies
- Part 3 (case study): delving deeper into the relationship of accommodation and comfort

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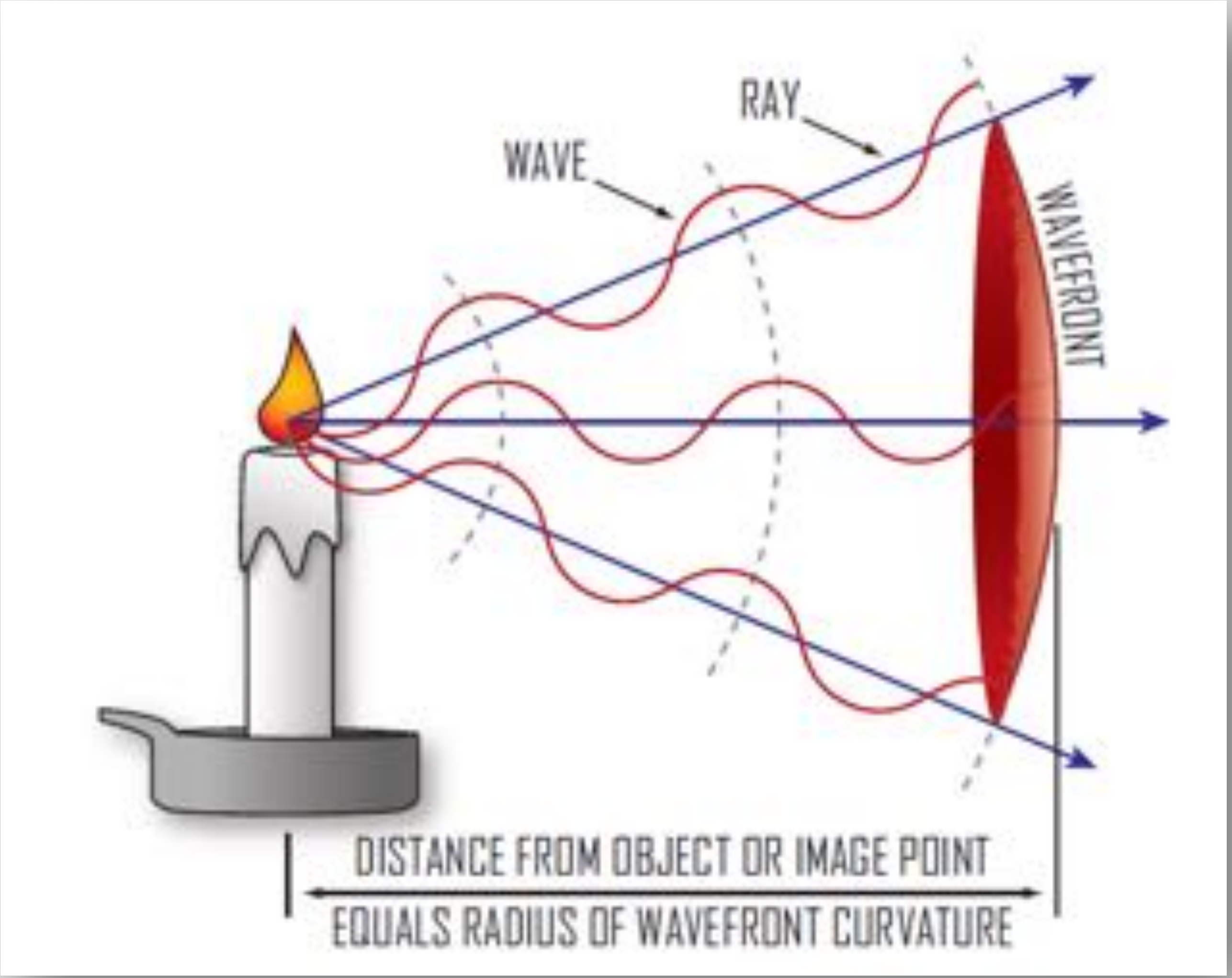
Part 1:
The basics

Light wave-front



Charle Laas

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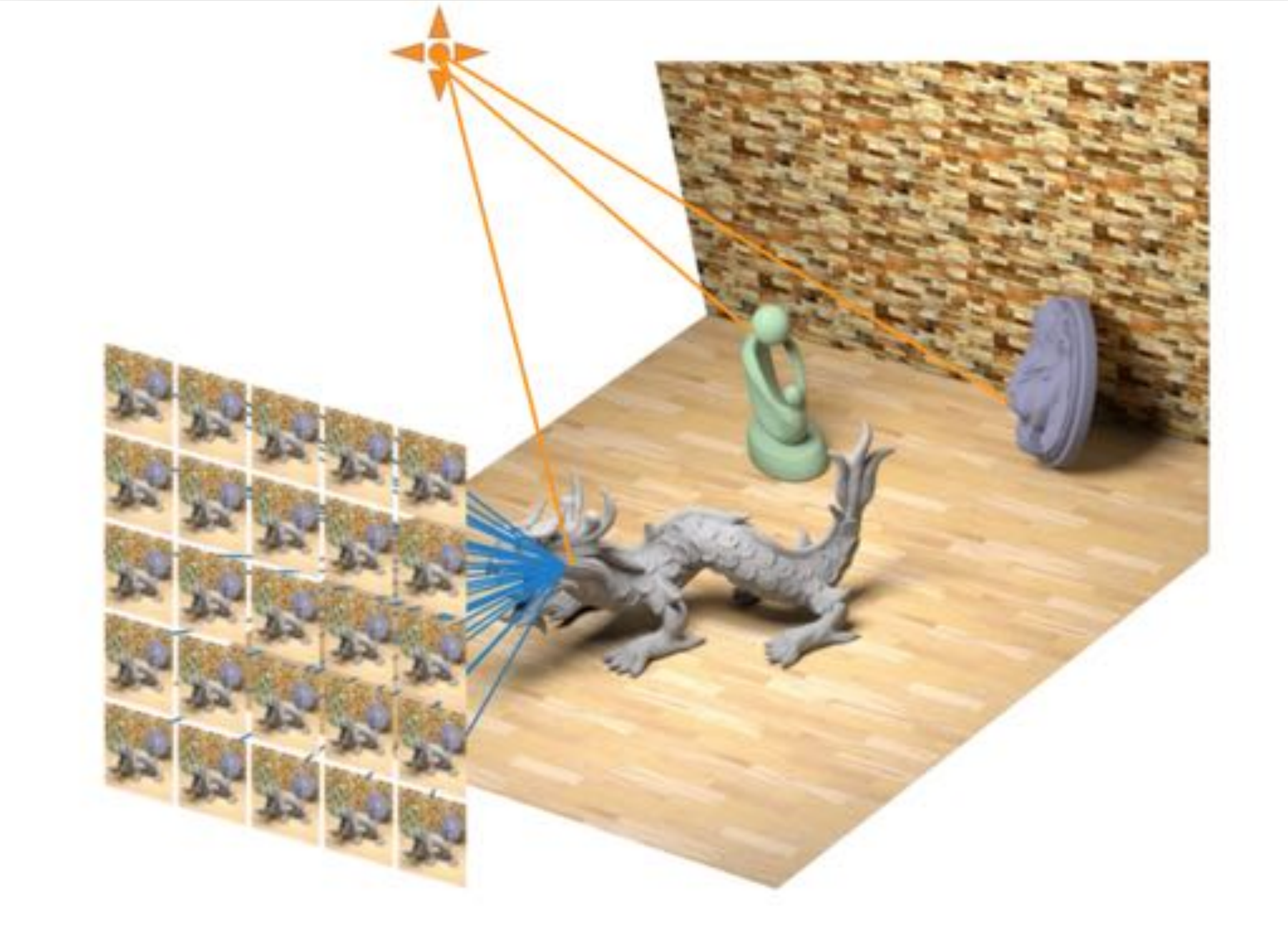
Natural light fields



Adapted from Mihara, 2016

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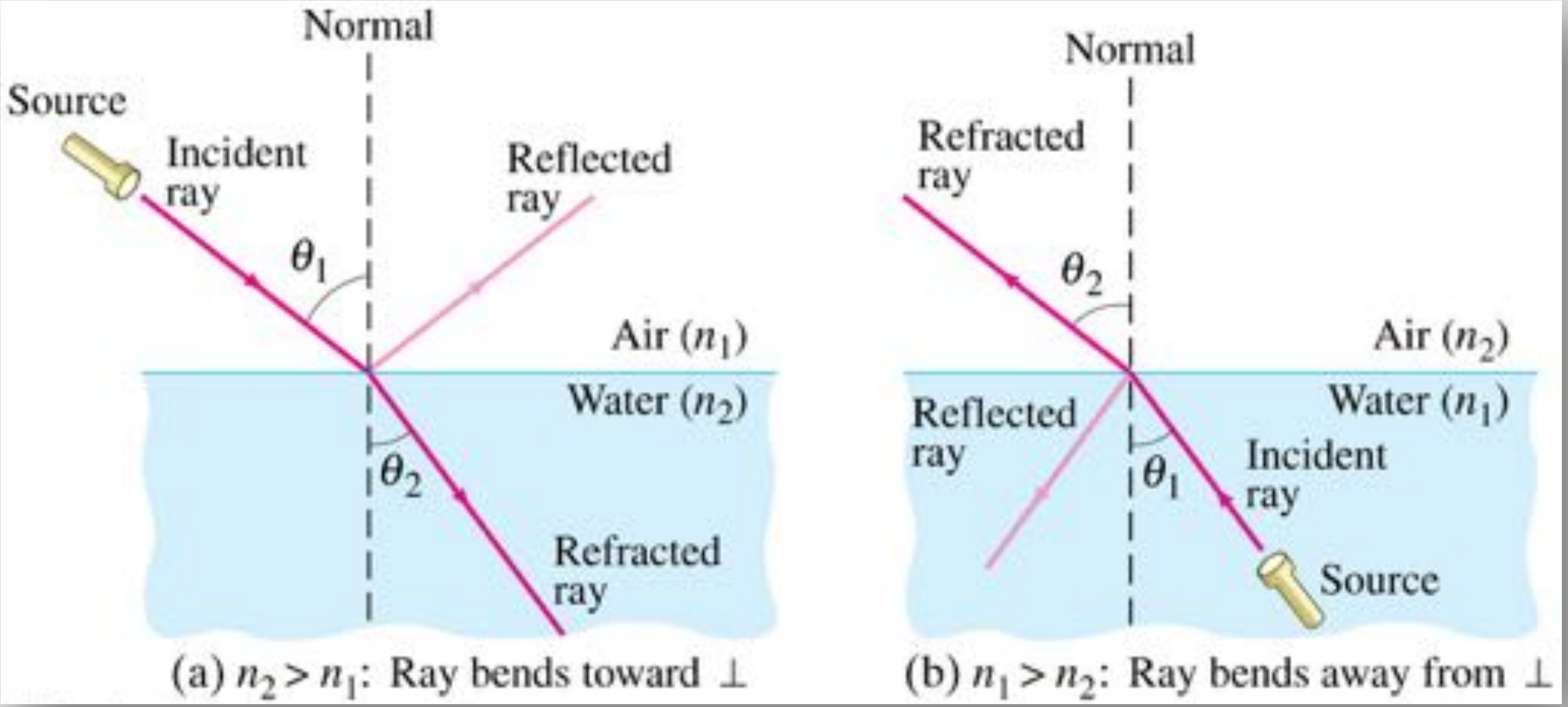
Refraction: Snell's law



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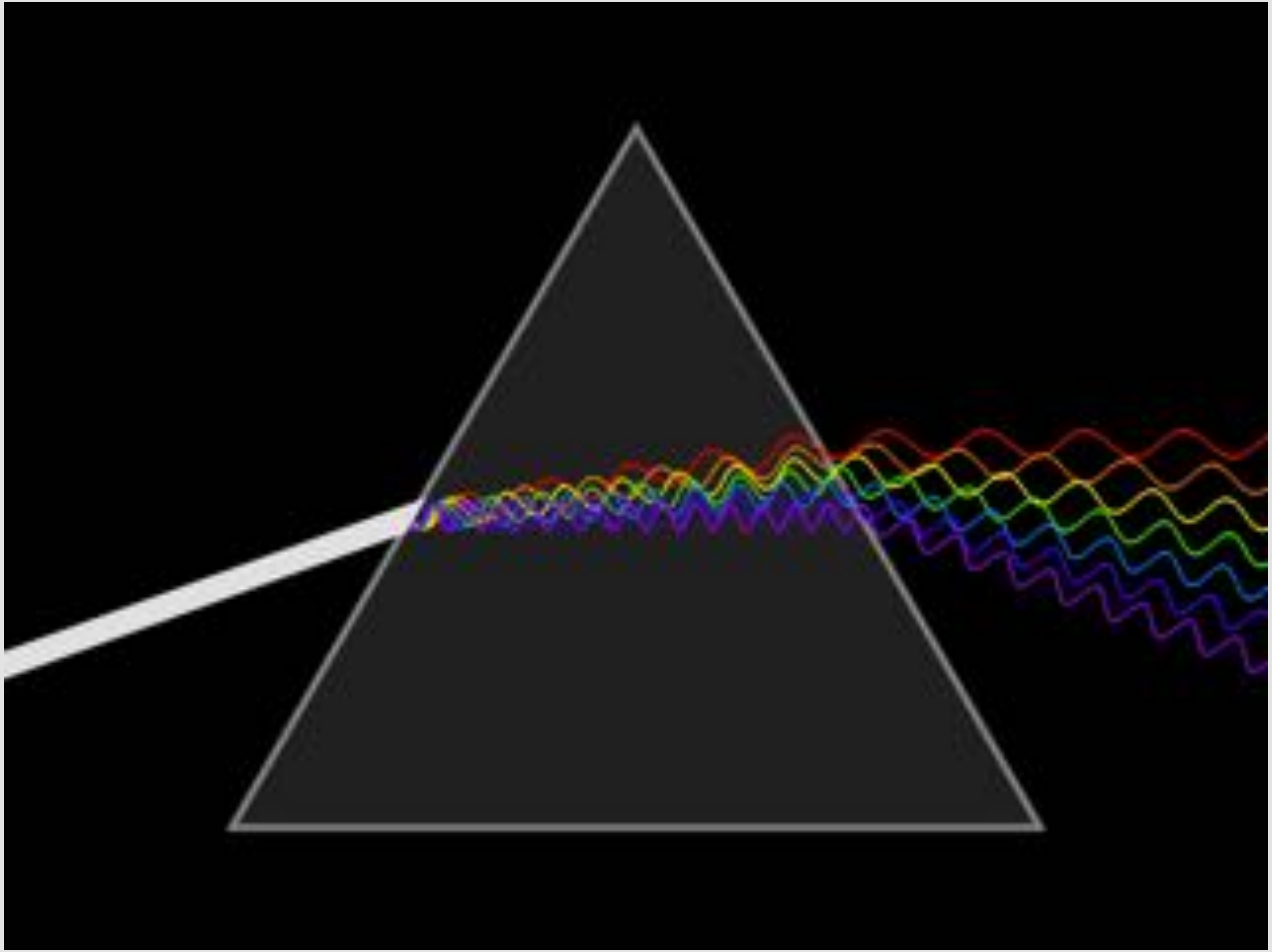
Wavelength dependent bending



Lucas Barbosa

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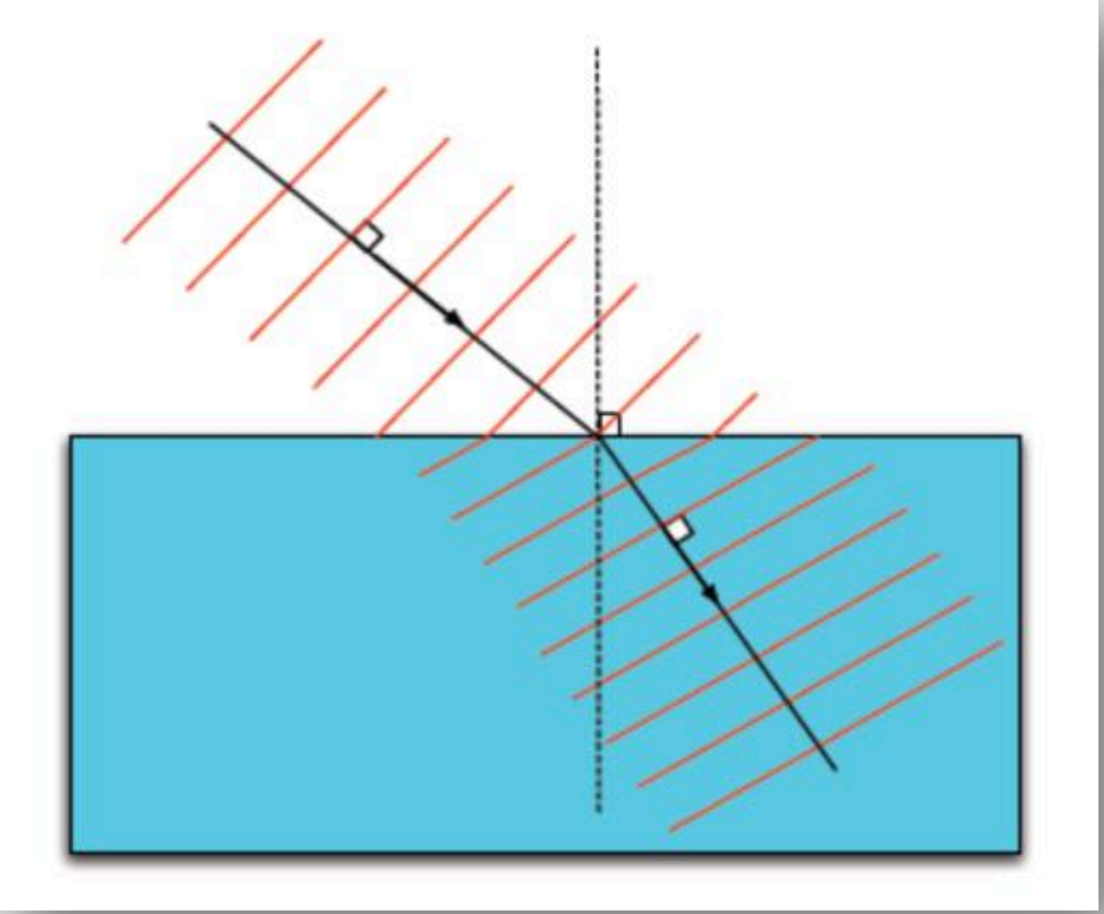
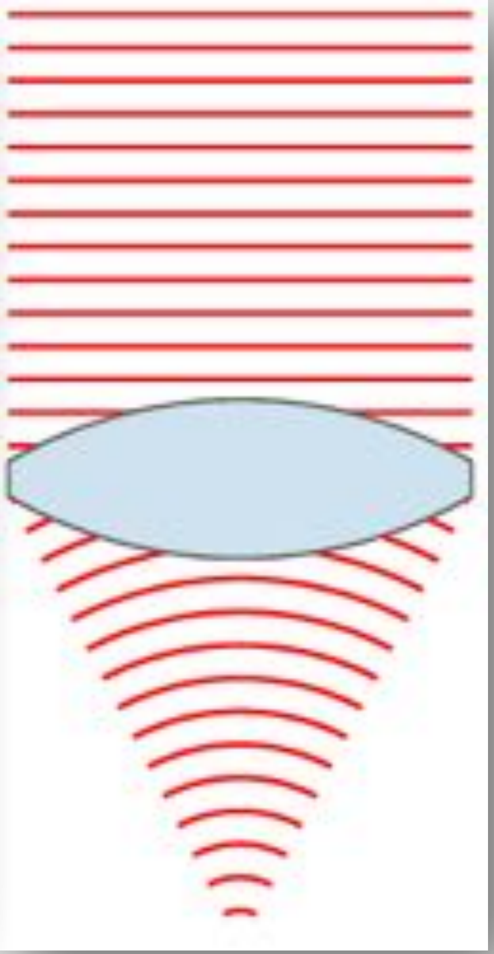
Light wave-front interacting with a lens



Libretexts



Oleg Alexandrov

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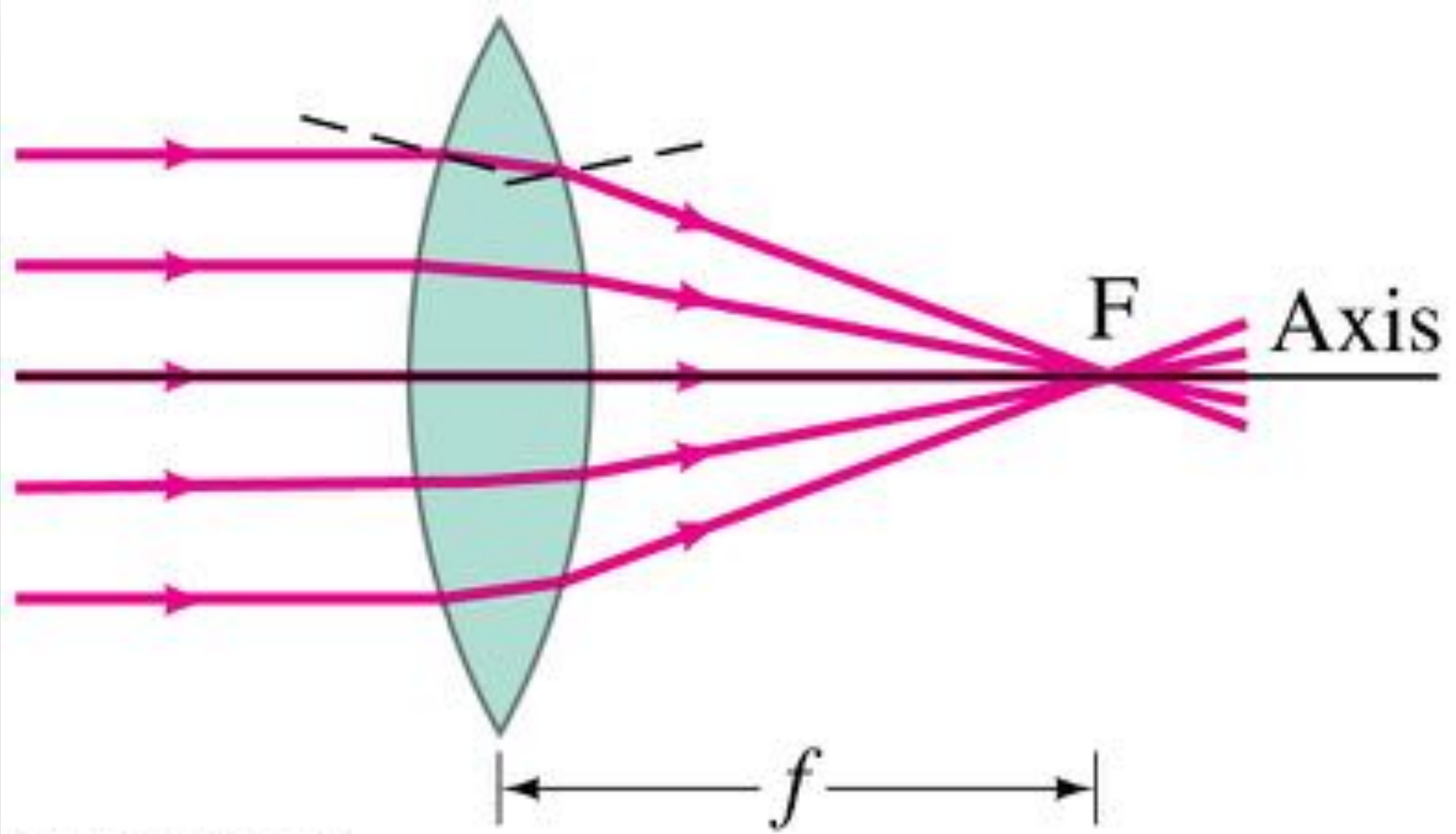
Convex thin lenses



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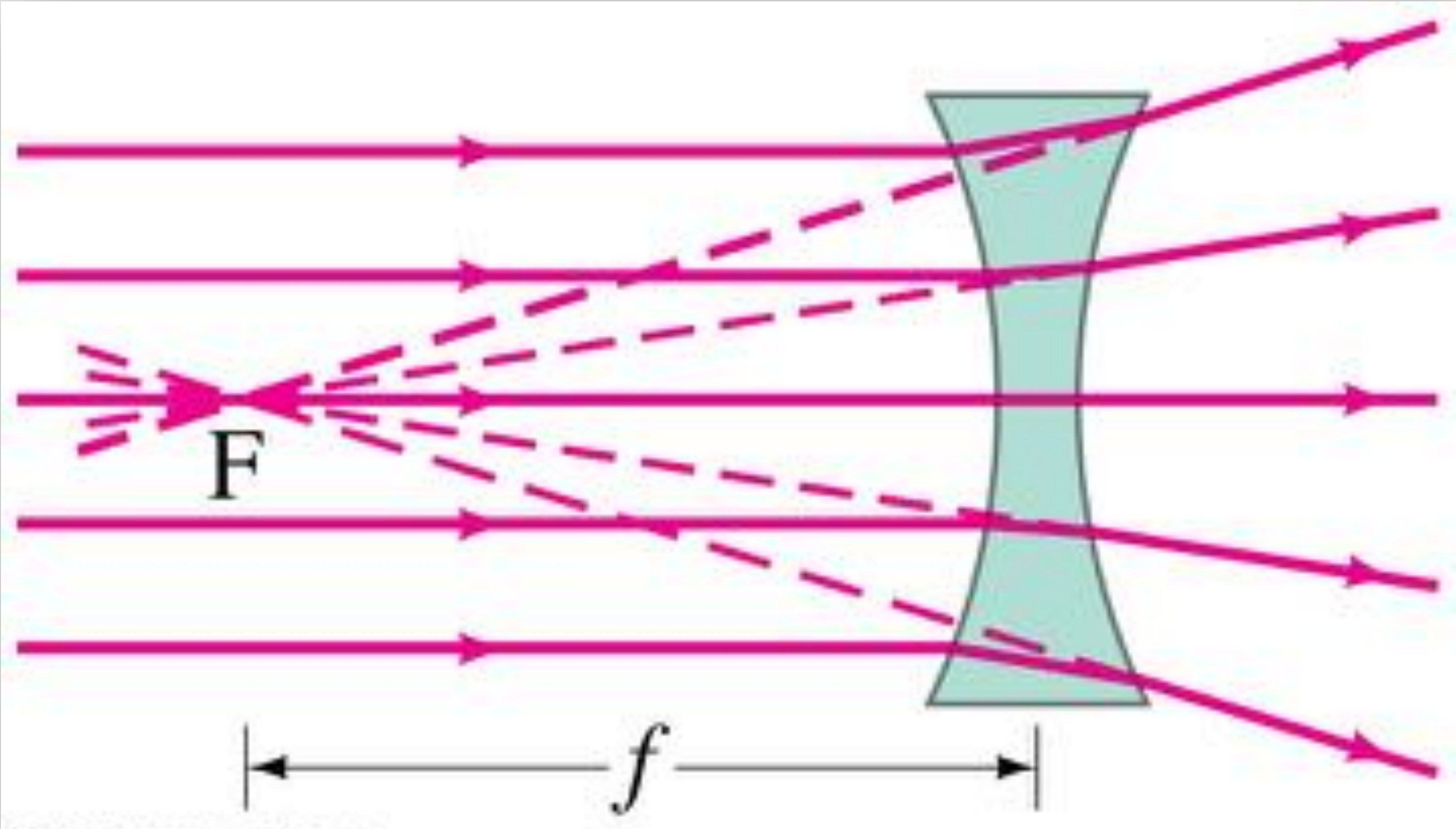
Concave thin lenses



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Dioptres

- Measurement unit of optical power
- Equal to the reciprocal of the focal length (in m)
- E.g., a 2-dioptre lens brings parallel rays of light to focus at 1 / 2 meter.
- E.g., a flat window has optical power of 0-dioptres
  - does not converge or diverge light.

Anatomy of the eye

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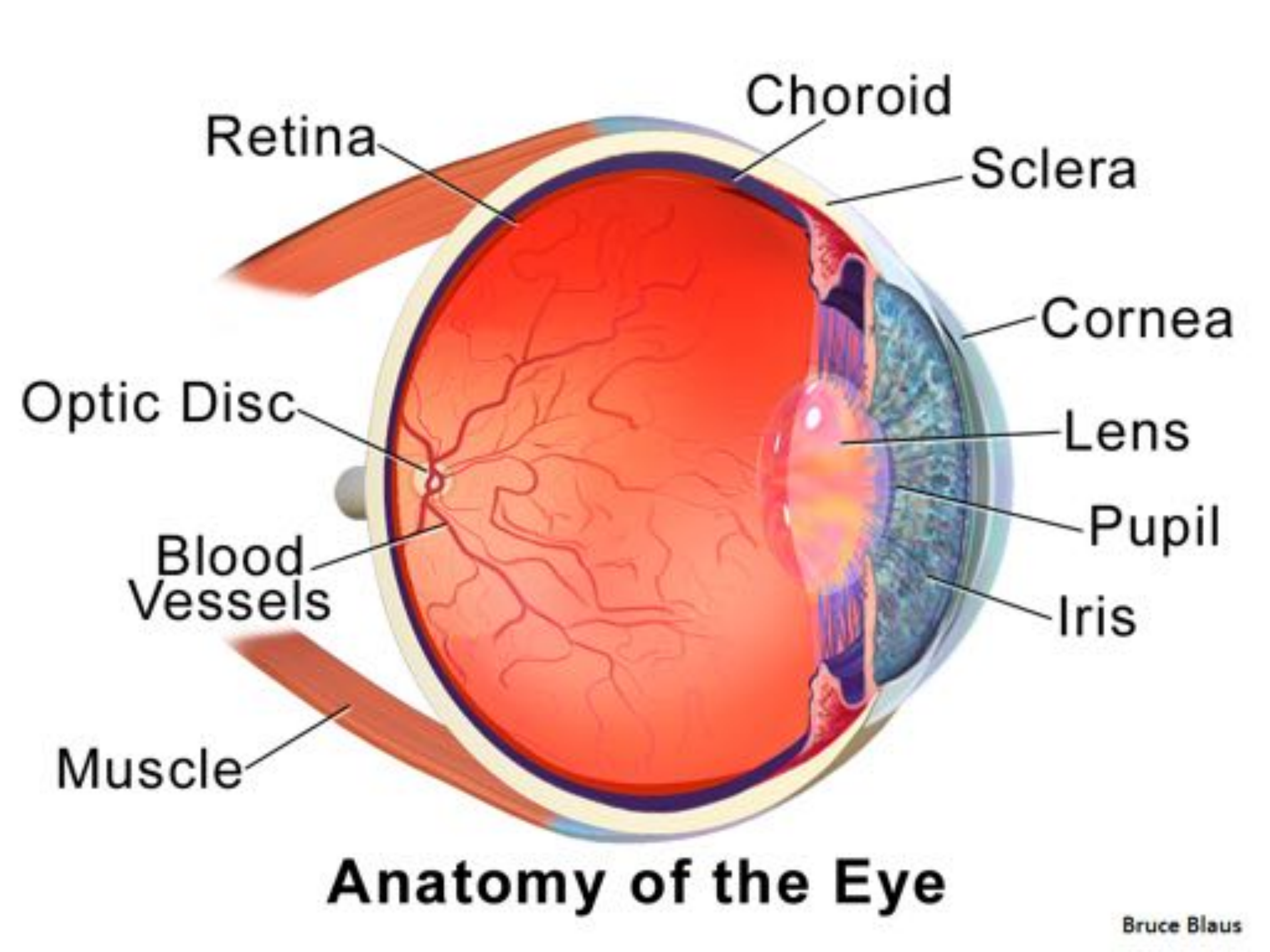
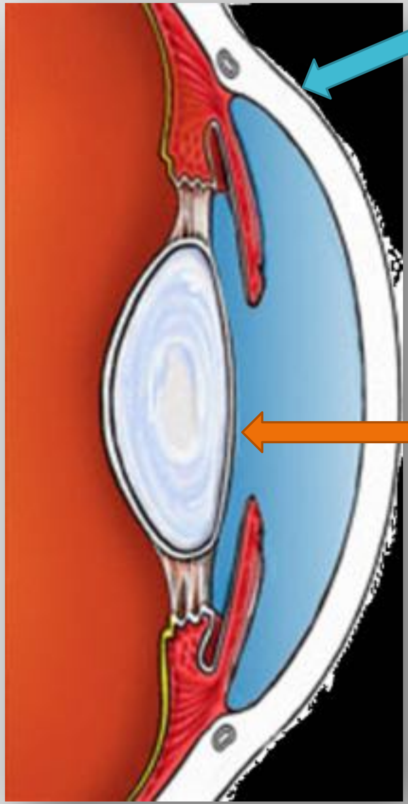
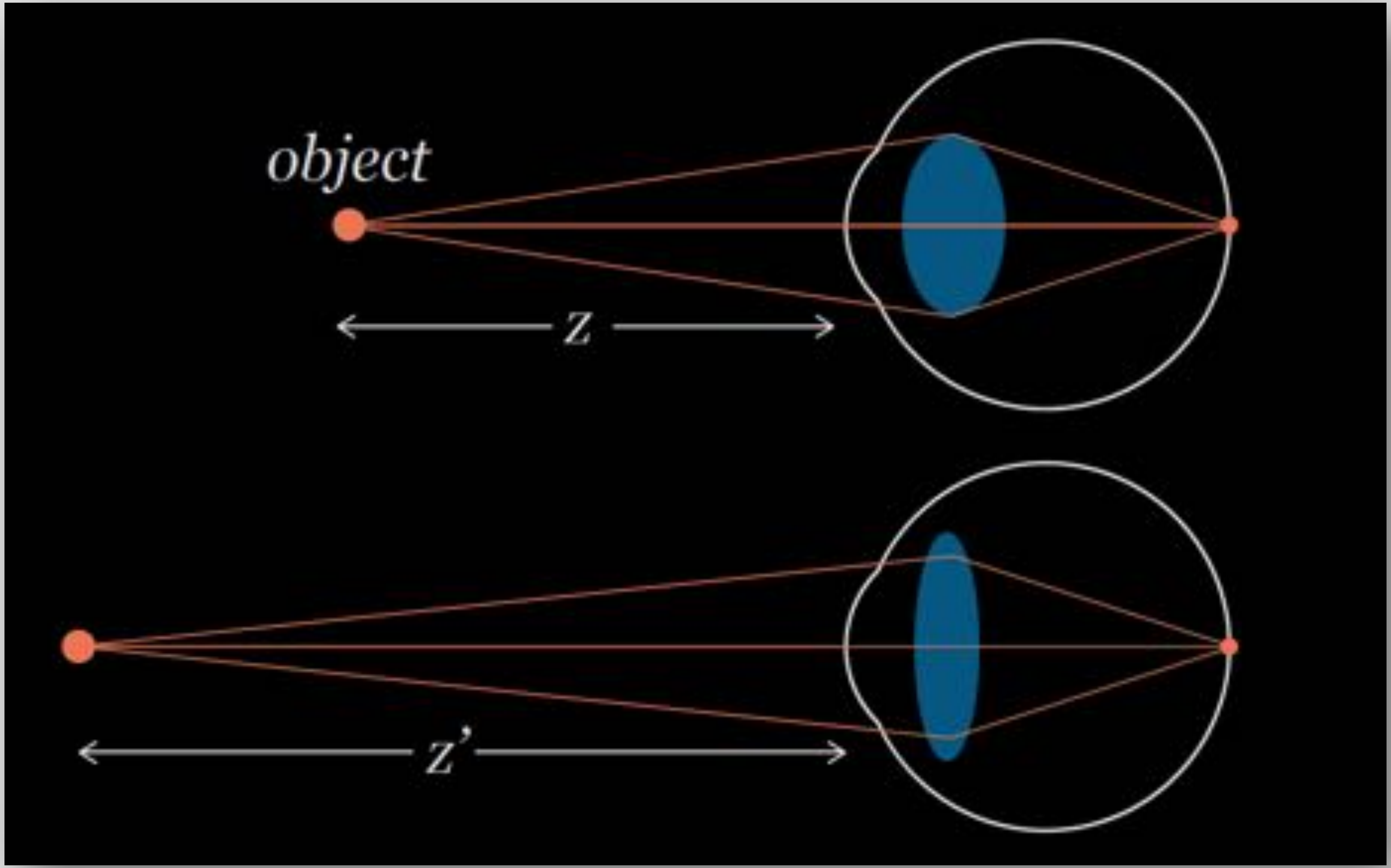


Two lenses in the eye



- Cornea
  - **fixed** power ~40 diopters
  - does most of the focusing
  - fun fact: focal length ≈ length of the eye
- Crystalline lens
  - **variable** up to ~20 diopters
  - power diminishes with age (presbyopia)
  - ~350 ms to change power

Accommodation



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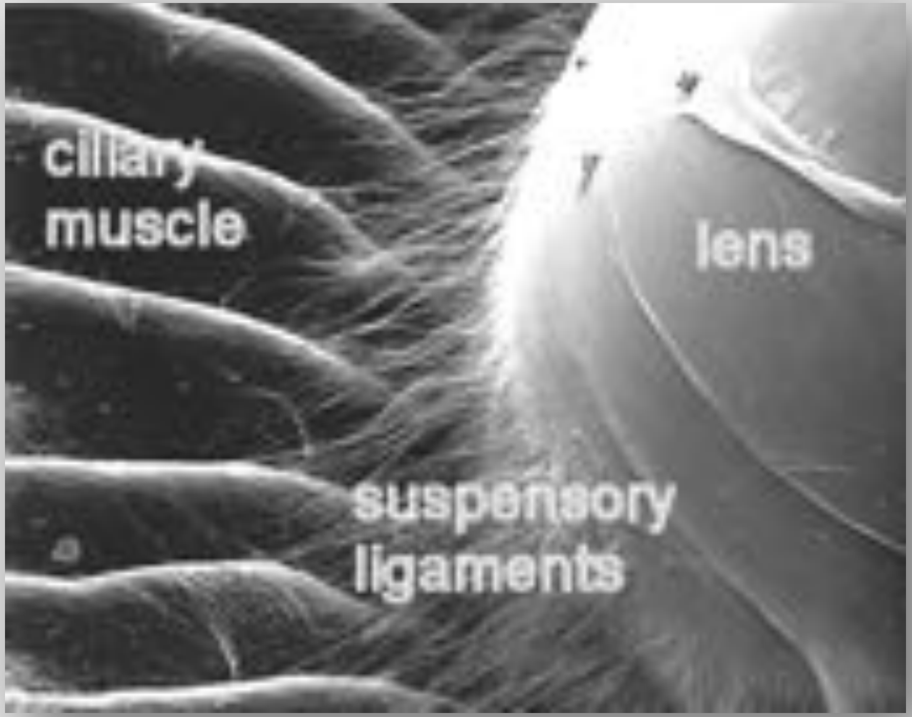
Fun fact: accommodation theories



Helmholtz Theory

When fixating a near object:

1. circularly arranged ciliary muscle contracts
2. lens zonules and suspensory ligaments relax
3. lens thickens

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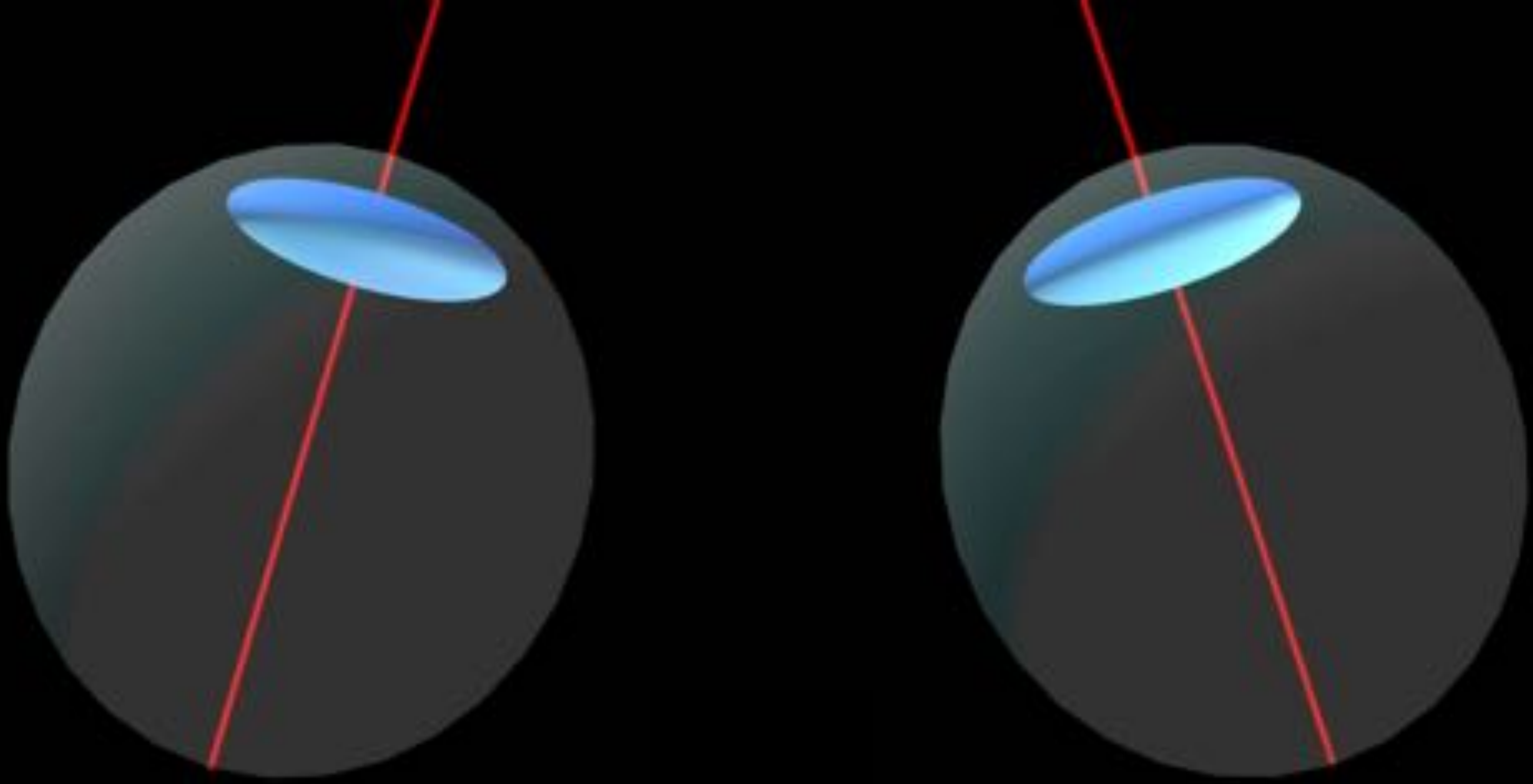
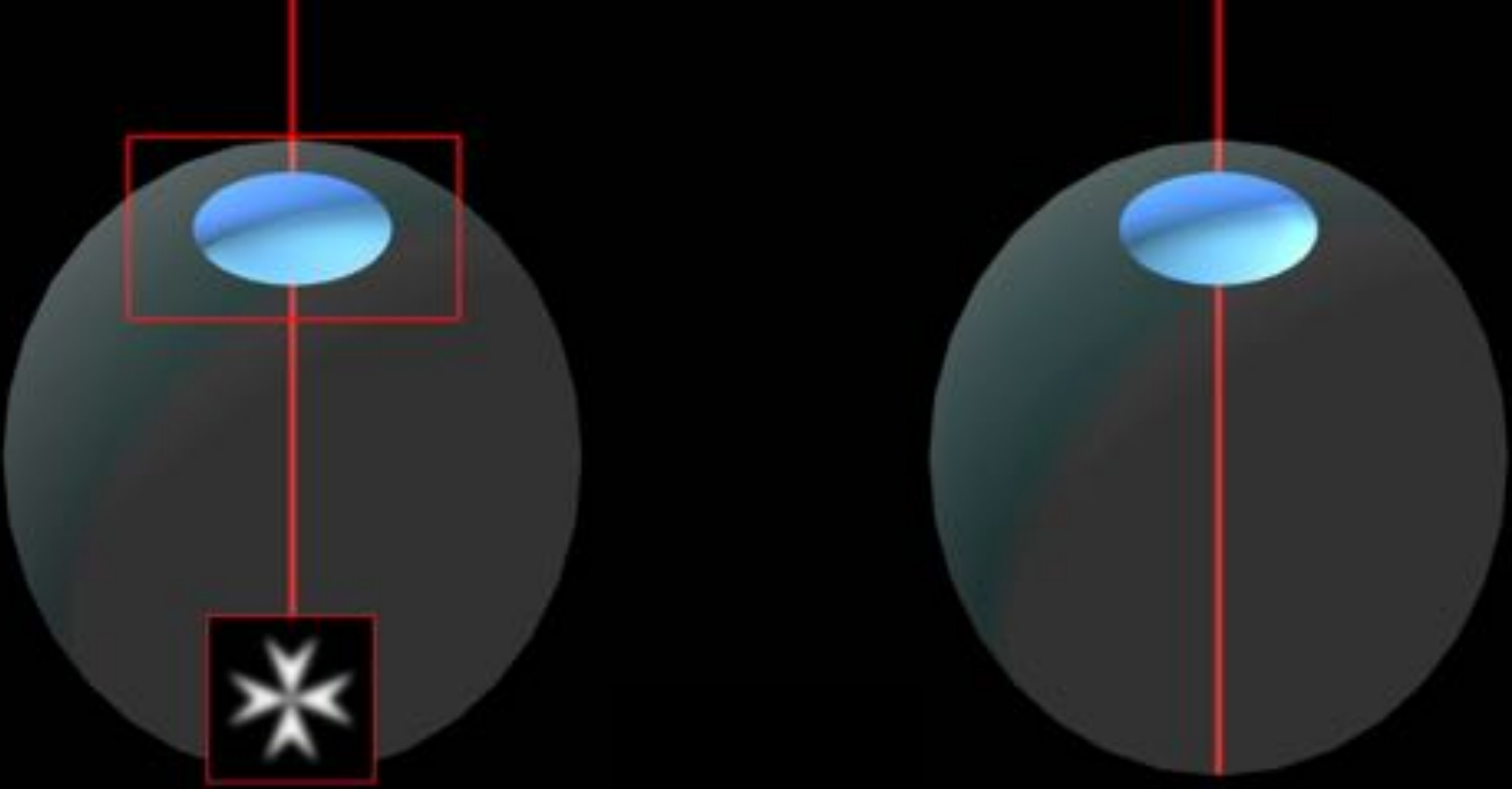
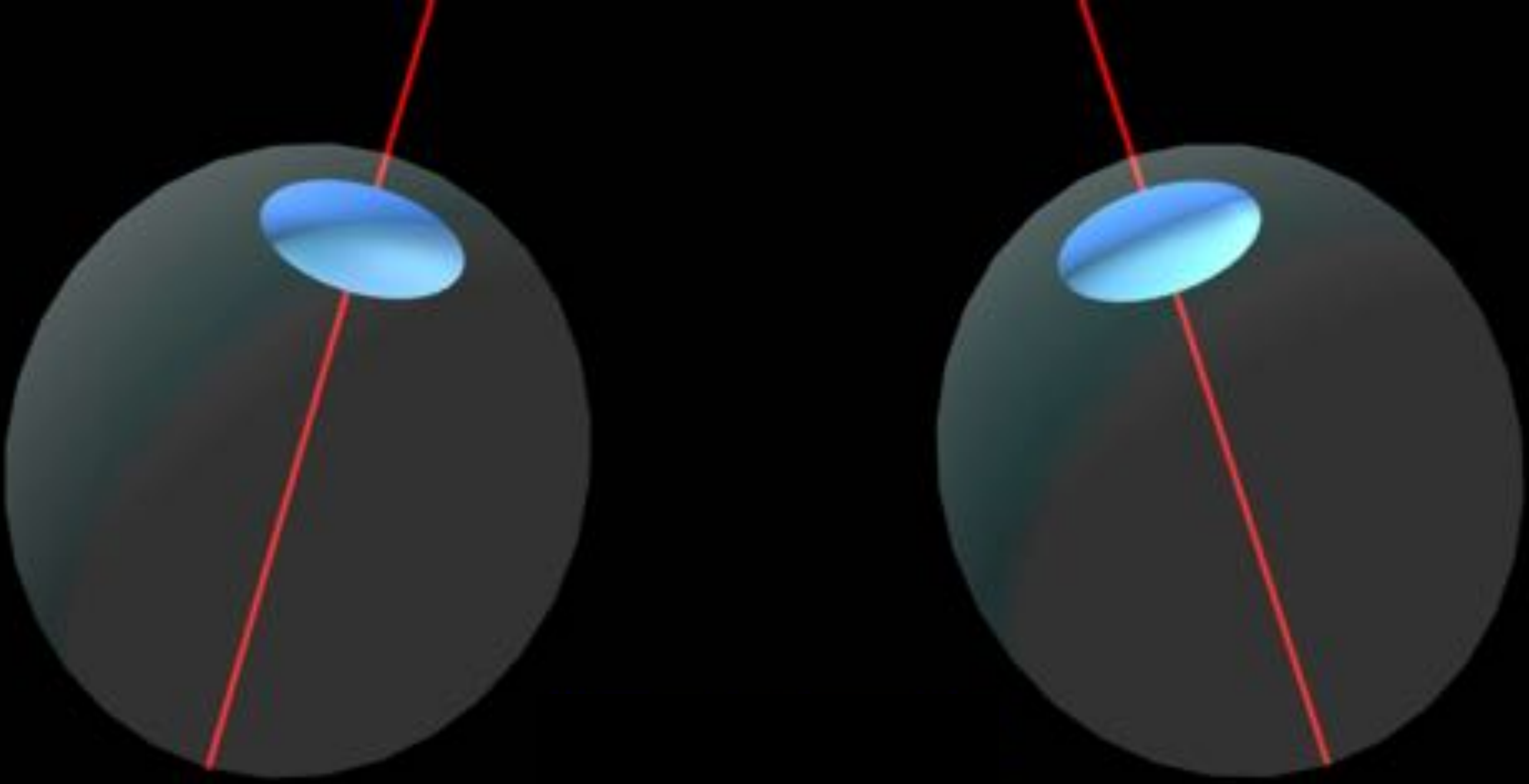
Now let us see how all this relate to a major source of discomfort in VR/AR



VERGENCE



ACCOMMODATION



COUPLED

Vergence and accommodation in the real world

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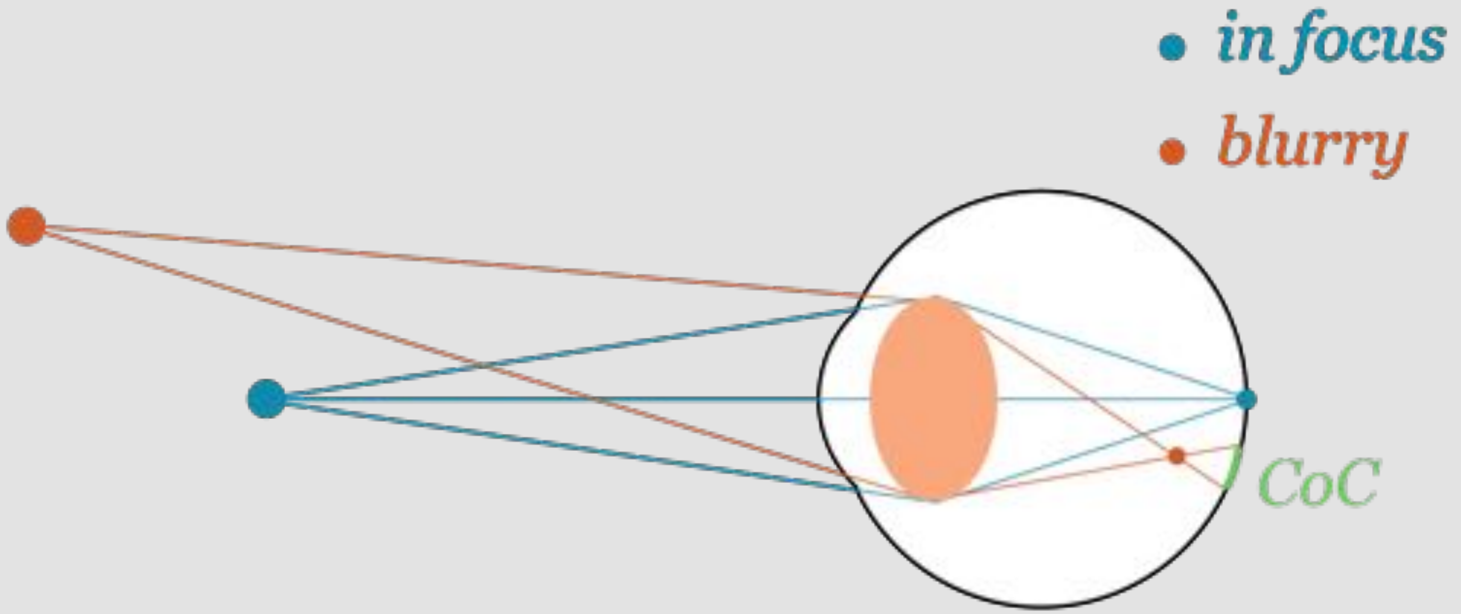
Blur in the real world



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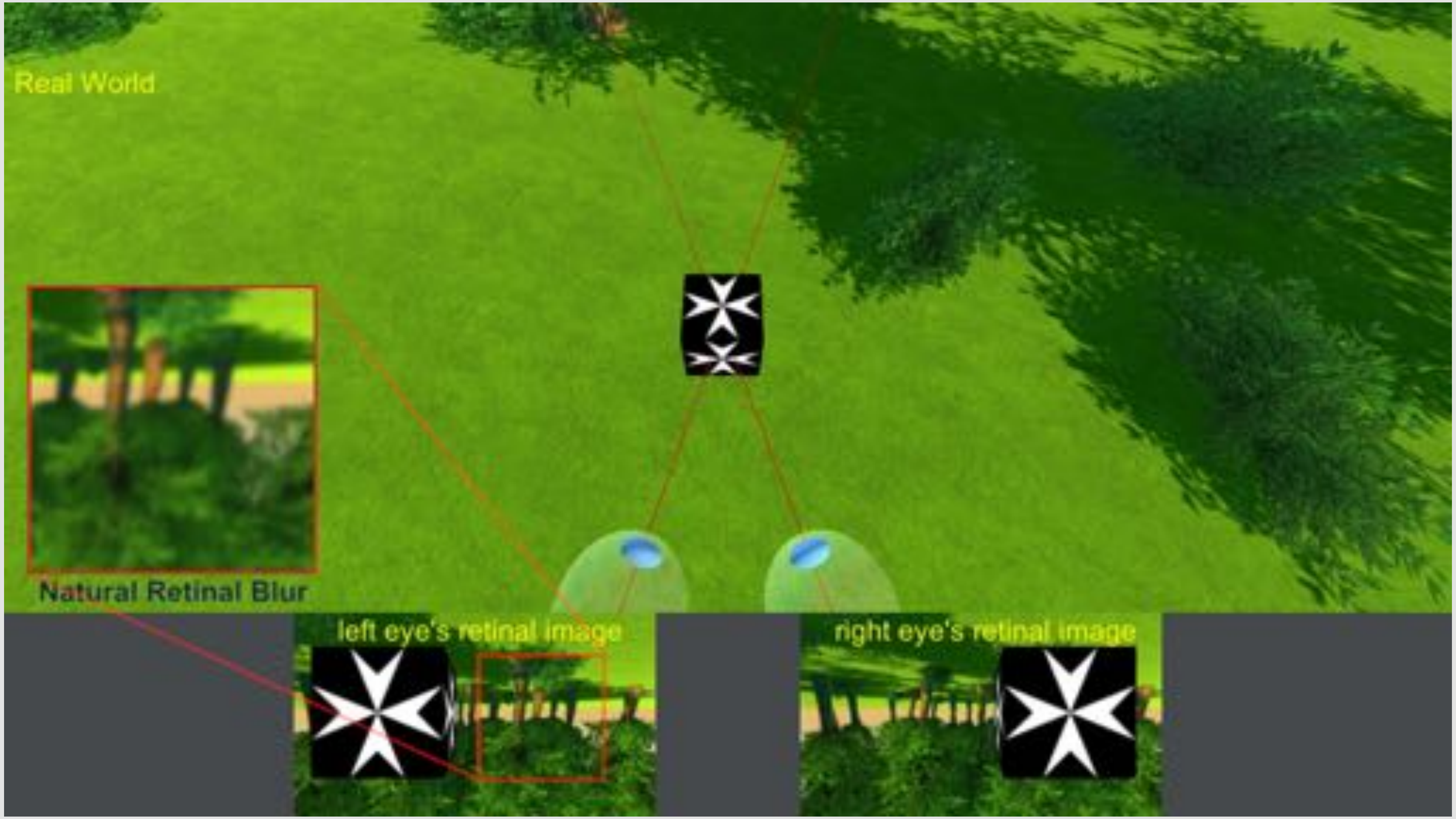
Blur in the real world



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But what about stereo displays ?

Vergence and accommodation conflicting in near-eye displays

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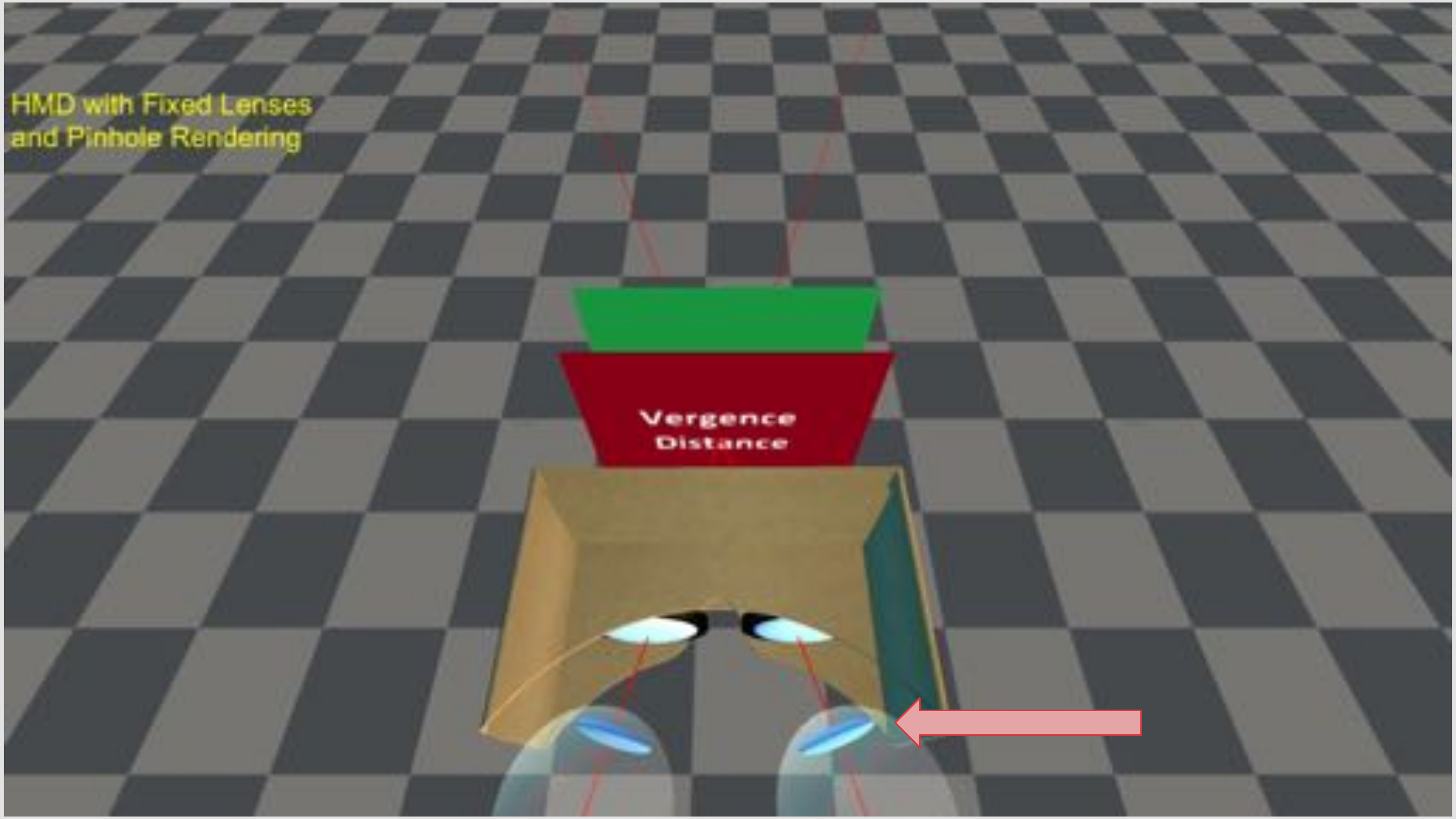
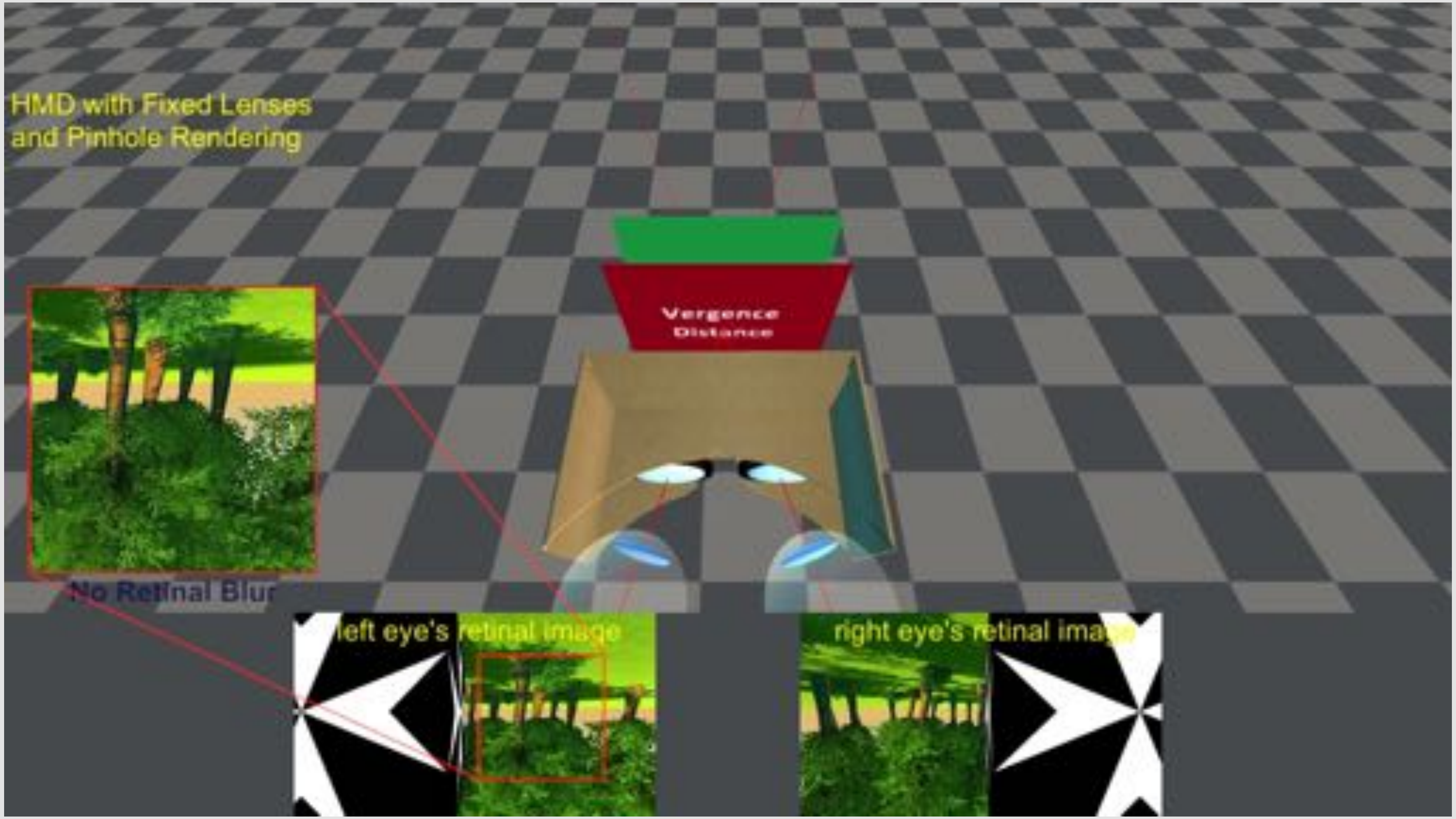


Blur non-existent in near-eye displays



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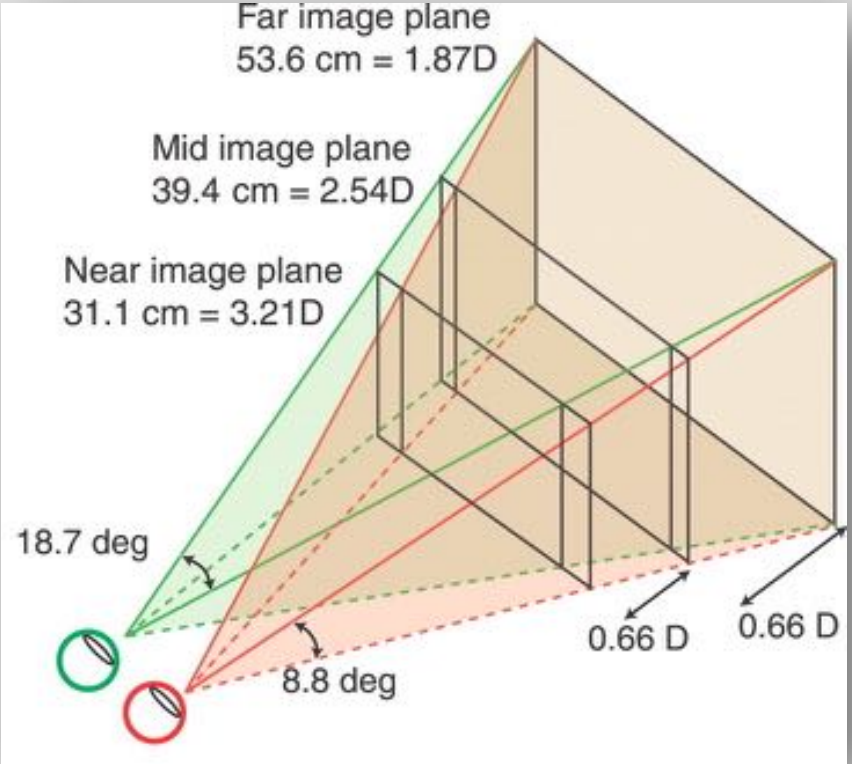
The VA conflict

1. No retinal blur
2. Accommodation generally does not match vergence

Viewer is required to fight against the natural coupling between accommodation and vergence which causes discomfort

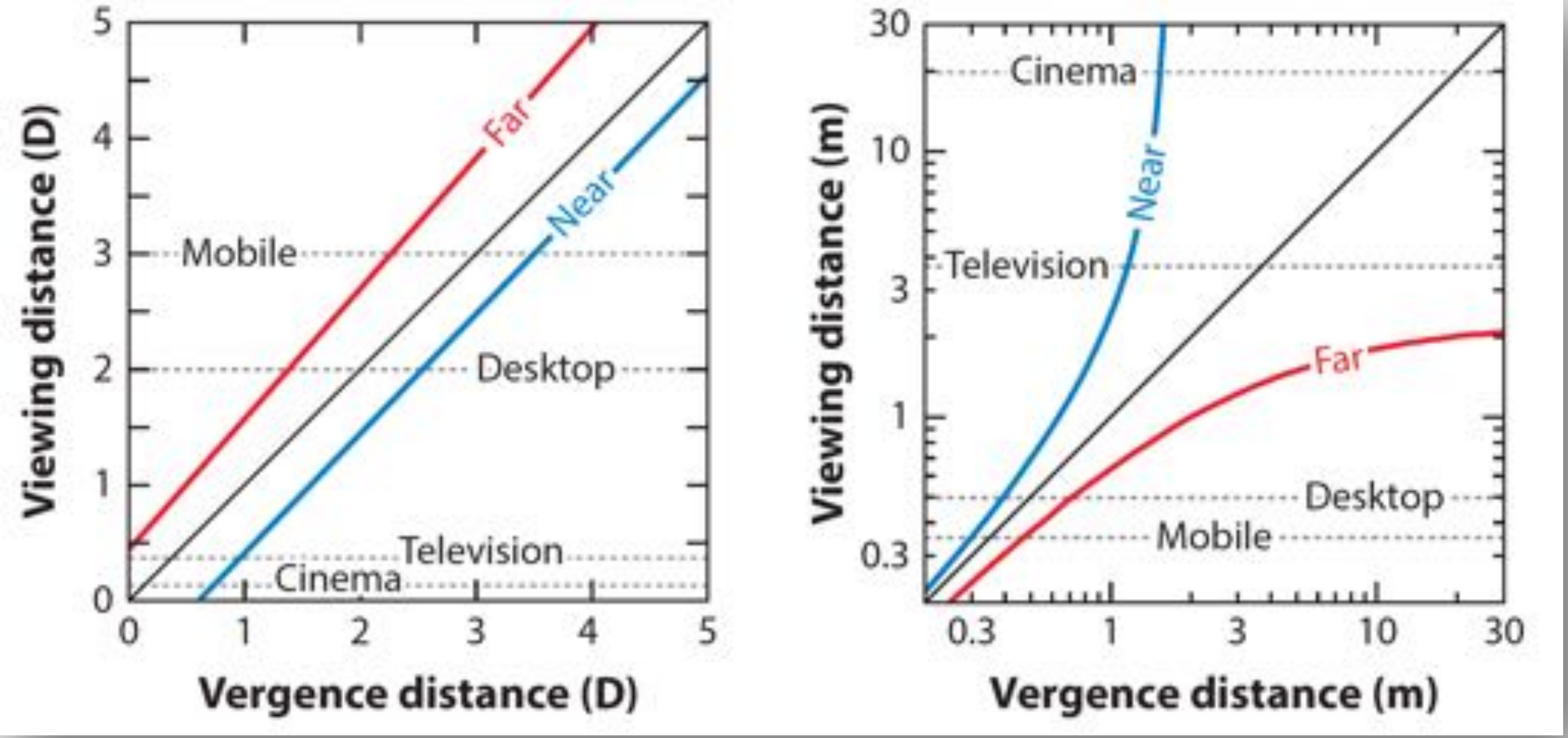
VA conflict is a major source of discomfort



Hoffman & Banks, 2010

Hoffman, D. M., Girshick, A. R., Akeley, K., & Banks, M. S. (2008). Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of vision*, *8*(3), 33-33.

VA conflict is a major source of discomfort



Shibata, T., Kim, J., Hoffman, D. M., & Banks, M. S. (2011). The zone of comfort: Predicting visual discomfort with stereo displays. *Journal of vision*, *11*(8), 11-11.

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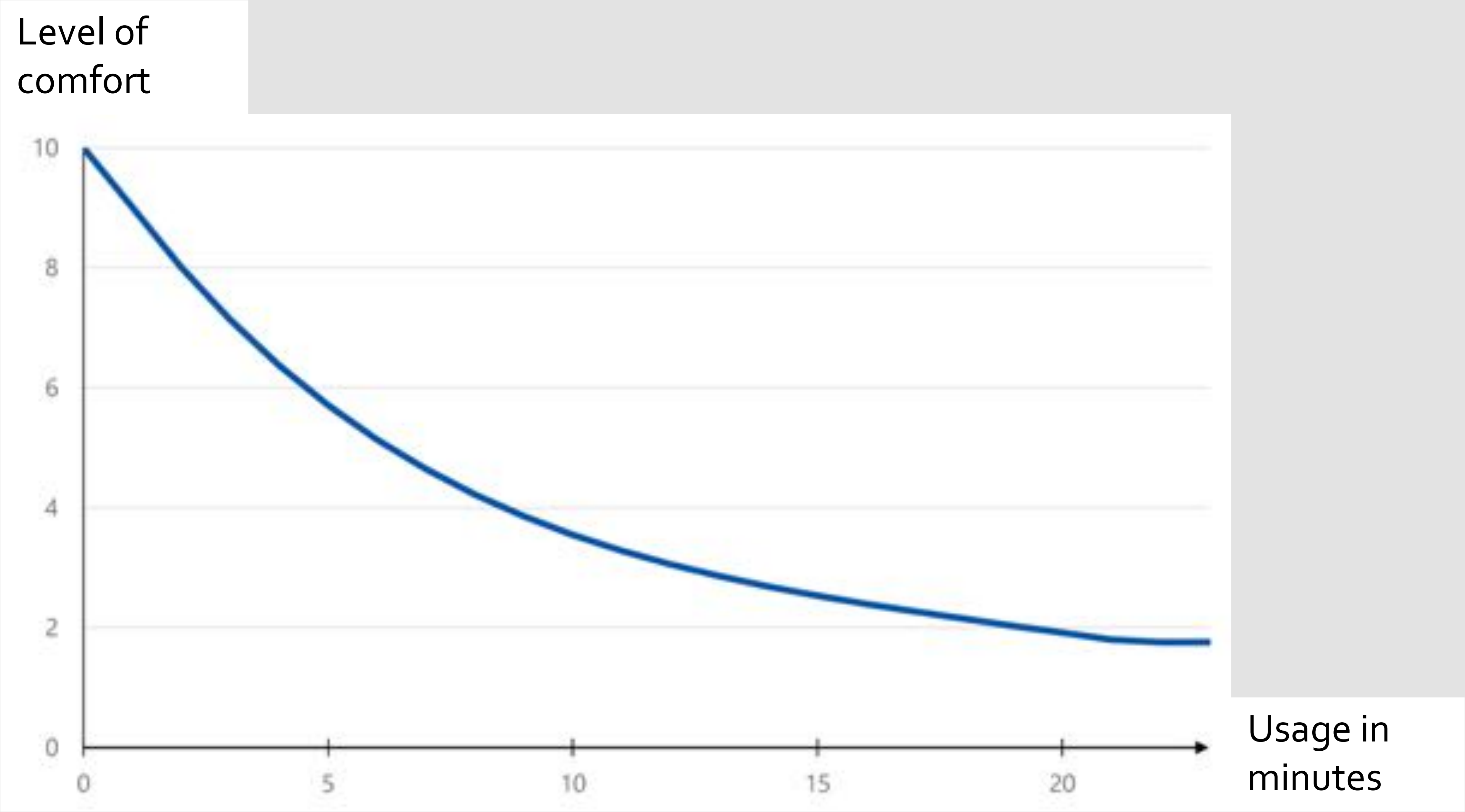
Comfort in VR, today



Fernandes and Feiner, 2016

VA conflict in presbyopes

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eye-trends.com

- Range of distances one can accommodate declines starting at the age of 40
- By 50/60 accommodative range is essentially zero
- Presbyopes are always in conflict ➔ used to it!
- No VA conflict due to stereoscopic viewing

Yang, S. N., Schlieski, T., Selmins, B., Cooper, S. C., Doherty, R. A., Corriveau, P. J., & Sheedy, J. E. (2012). Stereoscopic viewing and reported perceived immersion and symptoms. *Optometry and vision science*, *89*(7), 1068-1080.

Lack of focus cues is not only affecting discomfort

- 3D shape perception
- Apparent scale of scenes
- Binocular performance

Buckley, D., & Frisby, J. P. (1993). Interaction of stereo, texture and outline cues in the shape perception of three-dimensional ridges. *Vision research*, *33*(7), 919-933.

Watt, S. J., Akeley, K., Ernst, M. O., & Banks, M. S. (2005). Focus cues affect perceived depth. *Journal of vision*, *5*(10), 7-7.

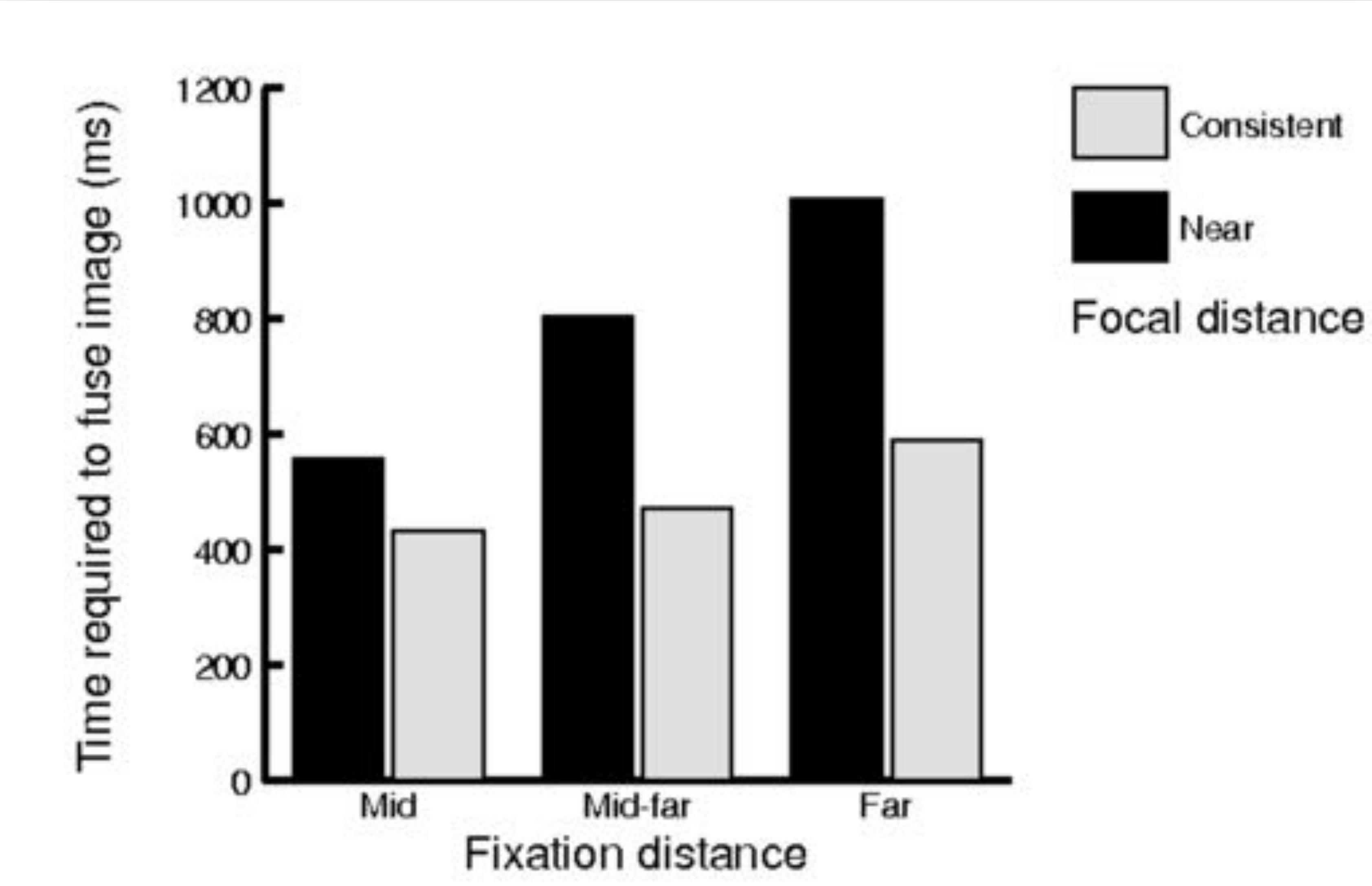
Focus cues affect perceived size of scenes

Held et al., 2010

Fielding R. 1985. Techniques of Special Effects Cinematography. Oxford, UK: Focal Press. 4th ed.

Held RT, Cooper EA, O'Brien JF, Banks MS. 2010. Using blur to affect perceived distance and size. ACM Trans. Graph. 29(2):19

Focus cues affect visual performance



Akeley, K., Watt, S. J., Girshick, A. R., & Banks, M. S. (2004, August). A stereo display prototype with multiple focal distances. In *ACM transactions on graphics (TOG)* (Vol. 23, No. 3, pp. 804-813). ACM.

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Fun facts: the iris

1. Reduces light by a factor of ~20
2. Constriction increases depth-of-field
3. Reduces spherical aberration by occluding outer parts of lens

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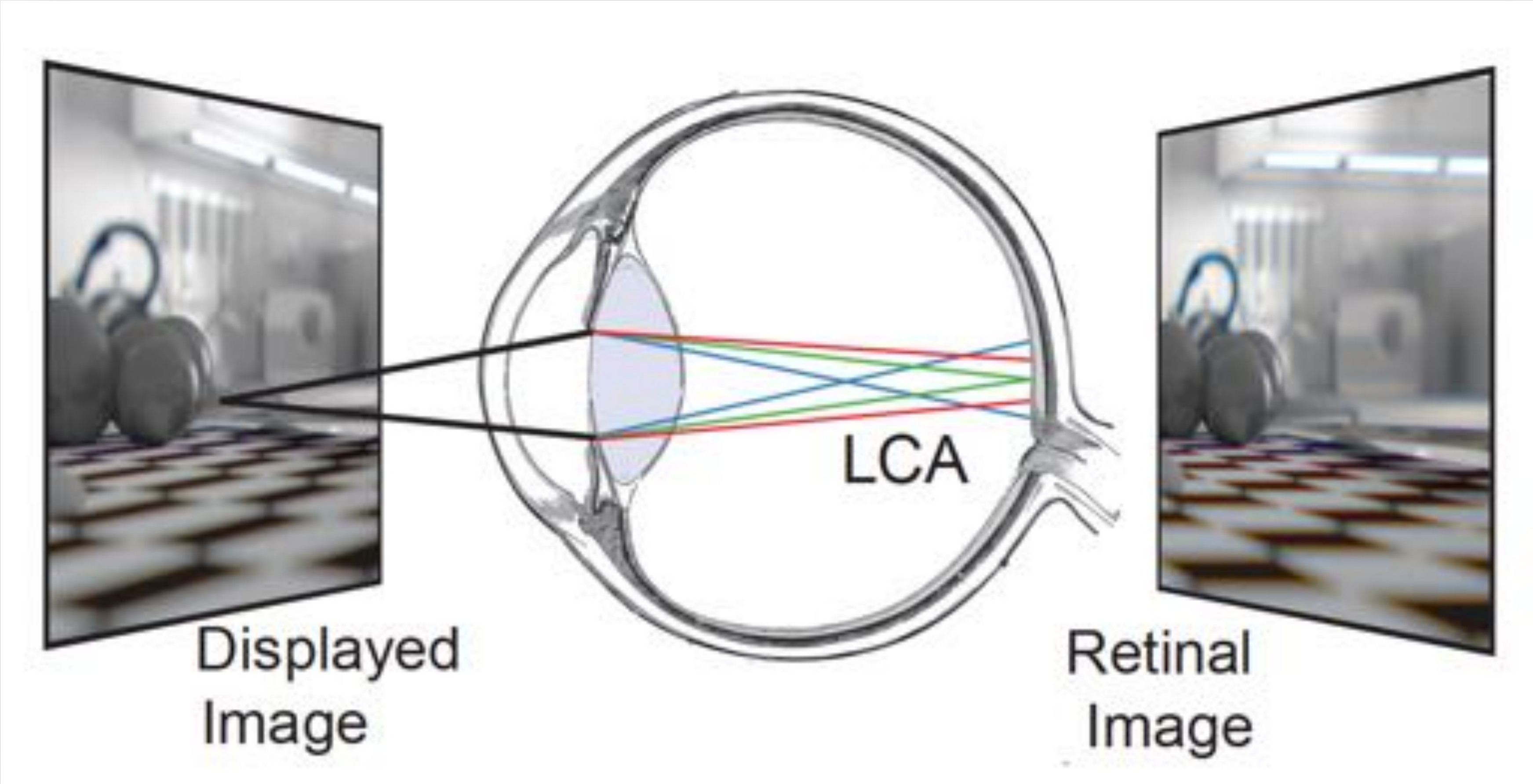
Fun fact: accommodation and the retina

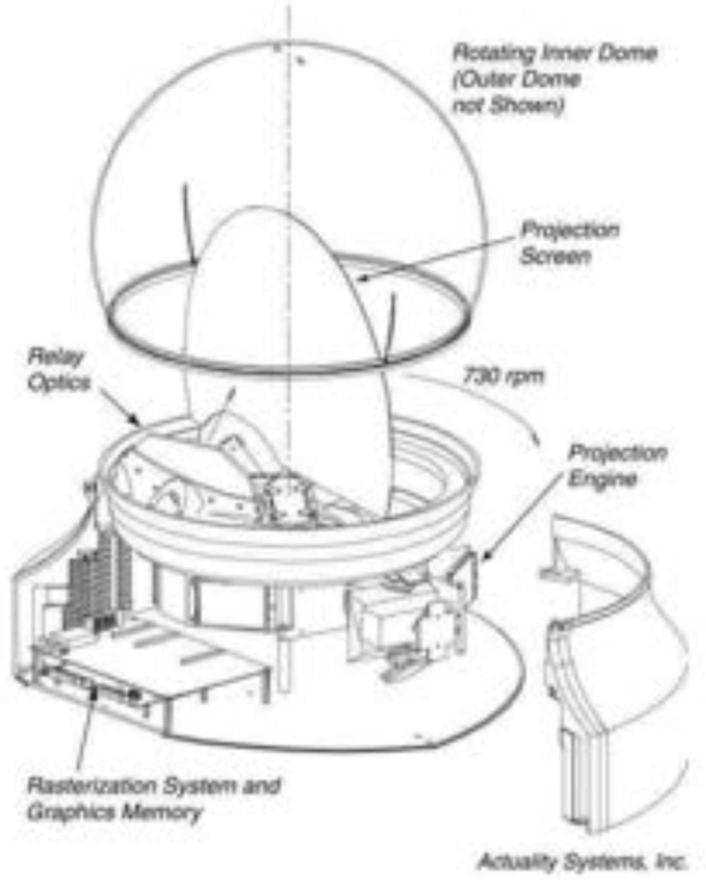


adapted from Cholewiak et al., 2017

- Infinitesimal amount of S-Cones ("blue") in the fovea
  - due to Longitudinal Chromatic Aberration?

Part 2:
Multifocal displays

Swept-screen volumetric displays



Favalora, G. E., Napoli, J., Hall, D. M., Dorval, R. K., Giovinco, M., Richmond, M. J., & Chun, W. S. (2002, August). 100-million-voxel volumetric display. In *Cockpit Displays IX: Displays for Defense Applications* (Vol. 4712, pp. 300-313). International Society for Optics and Photonics.

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Swept-screen volumetric displays

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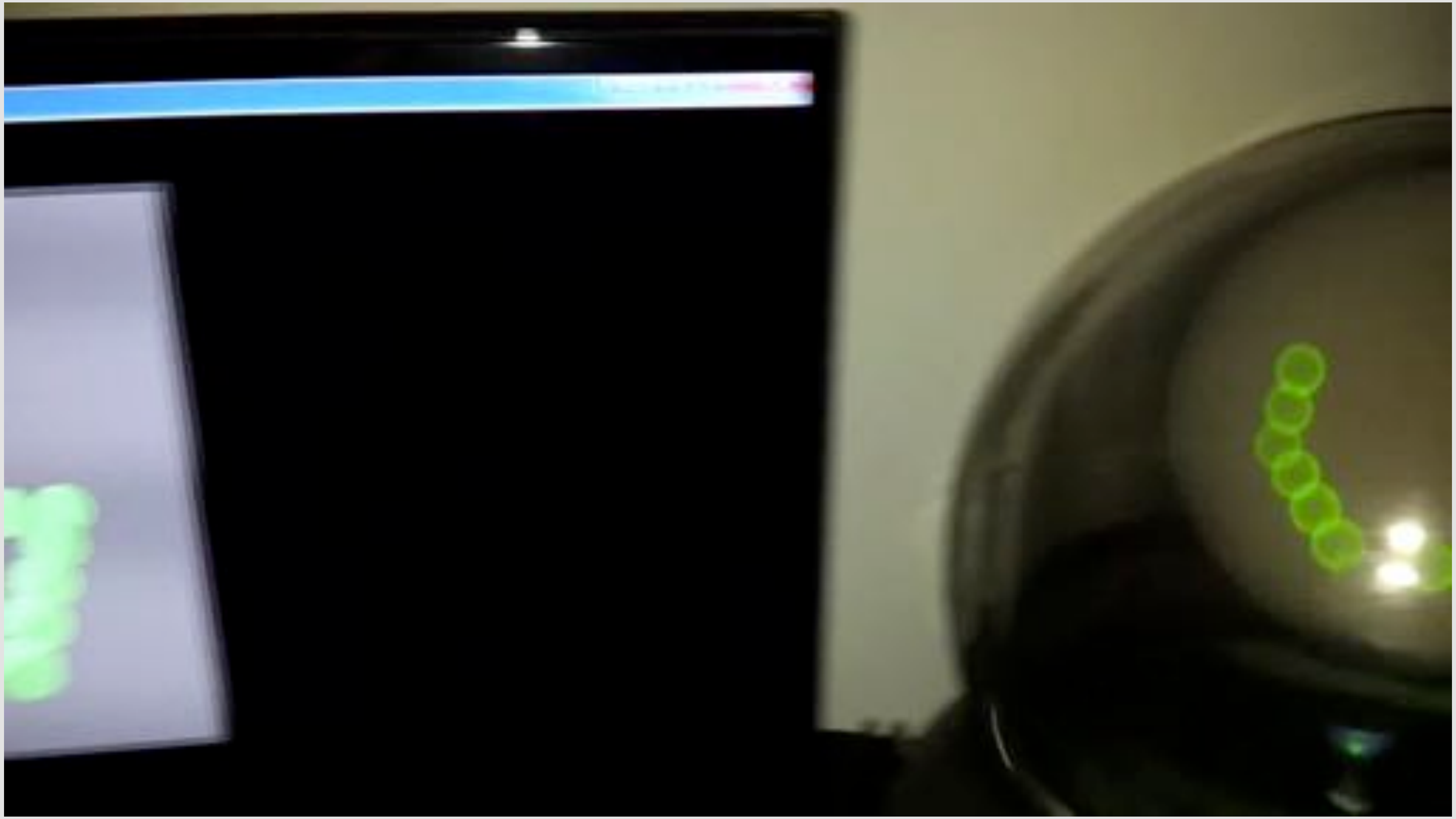
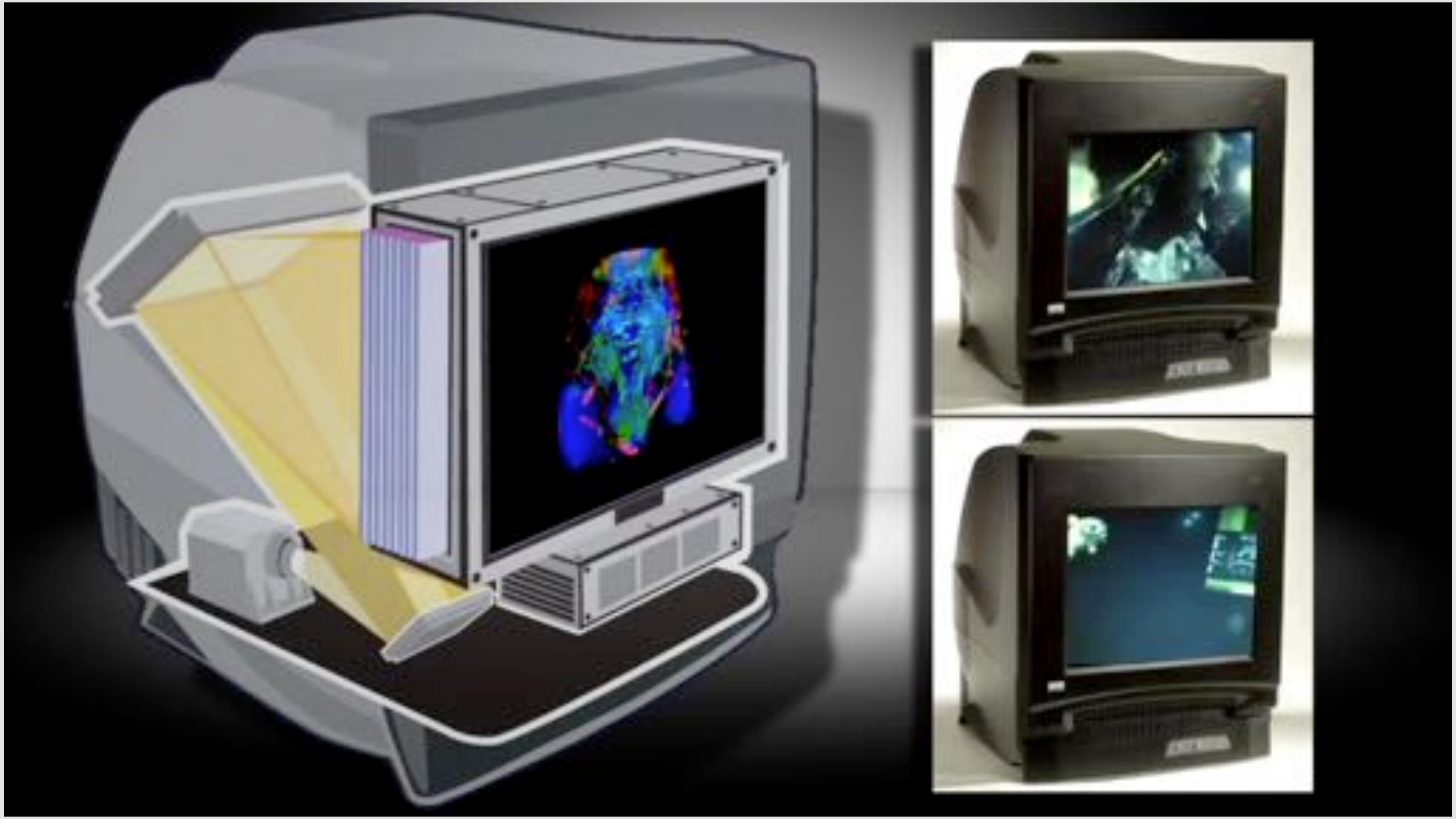


Abhijit Karnik

Stacked-screen volumetric displays

Sullivan, A. (2004, May). DepthCube solid-state 3D volumetric display.
In *Stereoscopic displays and virtual reality systems XI*(Vol. 5291, pp. 279-285).
International Society for Optics and Photonics.

Stacked-screen volumetric displays



LightSpace Technologies

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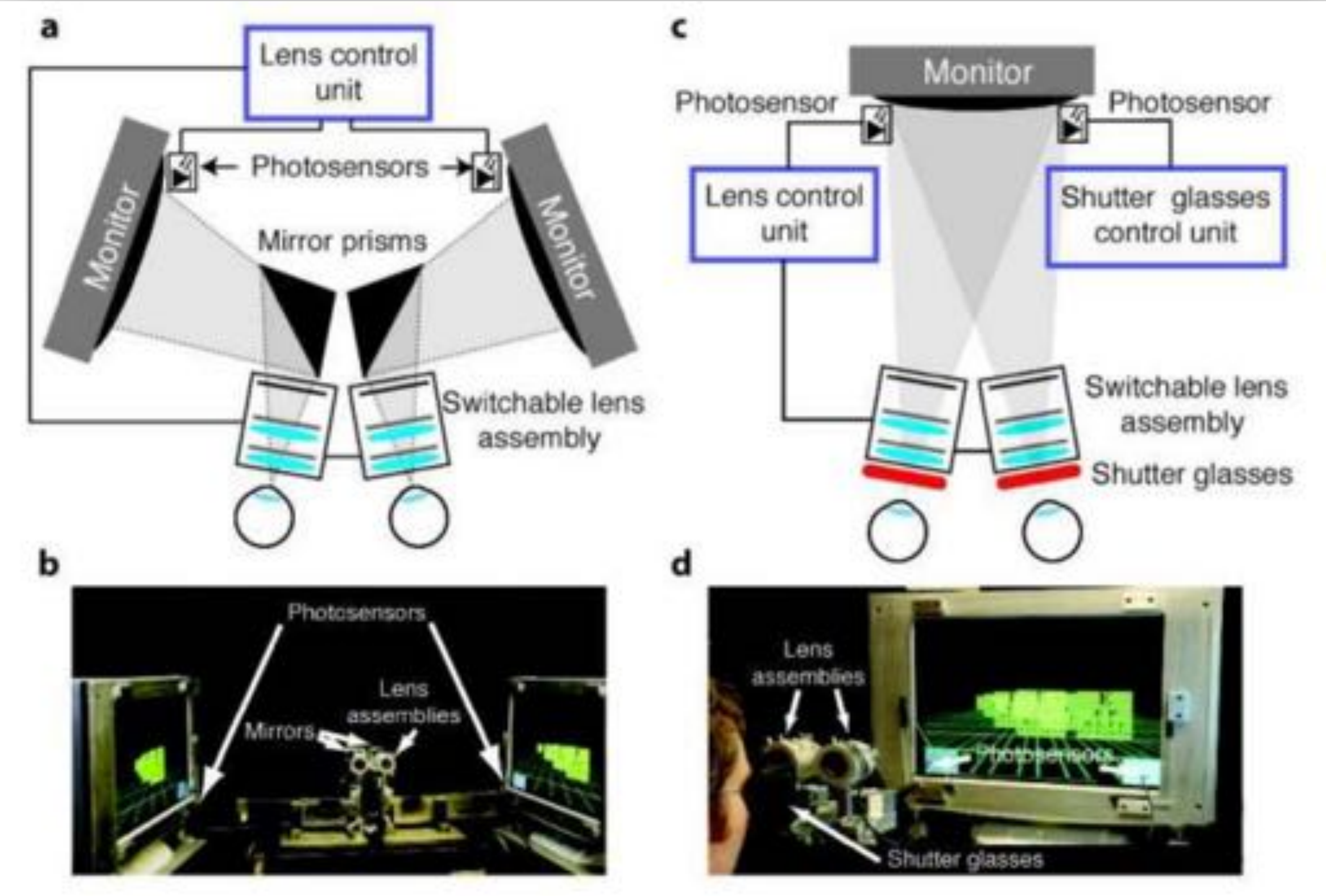
Advantages & disadvantages

- Present correct stereo, parallax and focus cues
- BUT
- Displayed scene confined to display volume
- Require computing and addressing a huge number of addressable voxels
- Cannot reproduce occlusions and viewpoint-dependent effects (e.g., reflections)

Fixed view-point volumetric displays



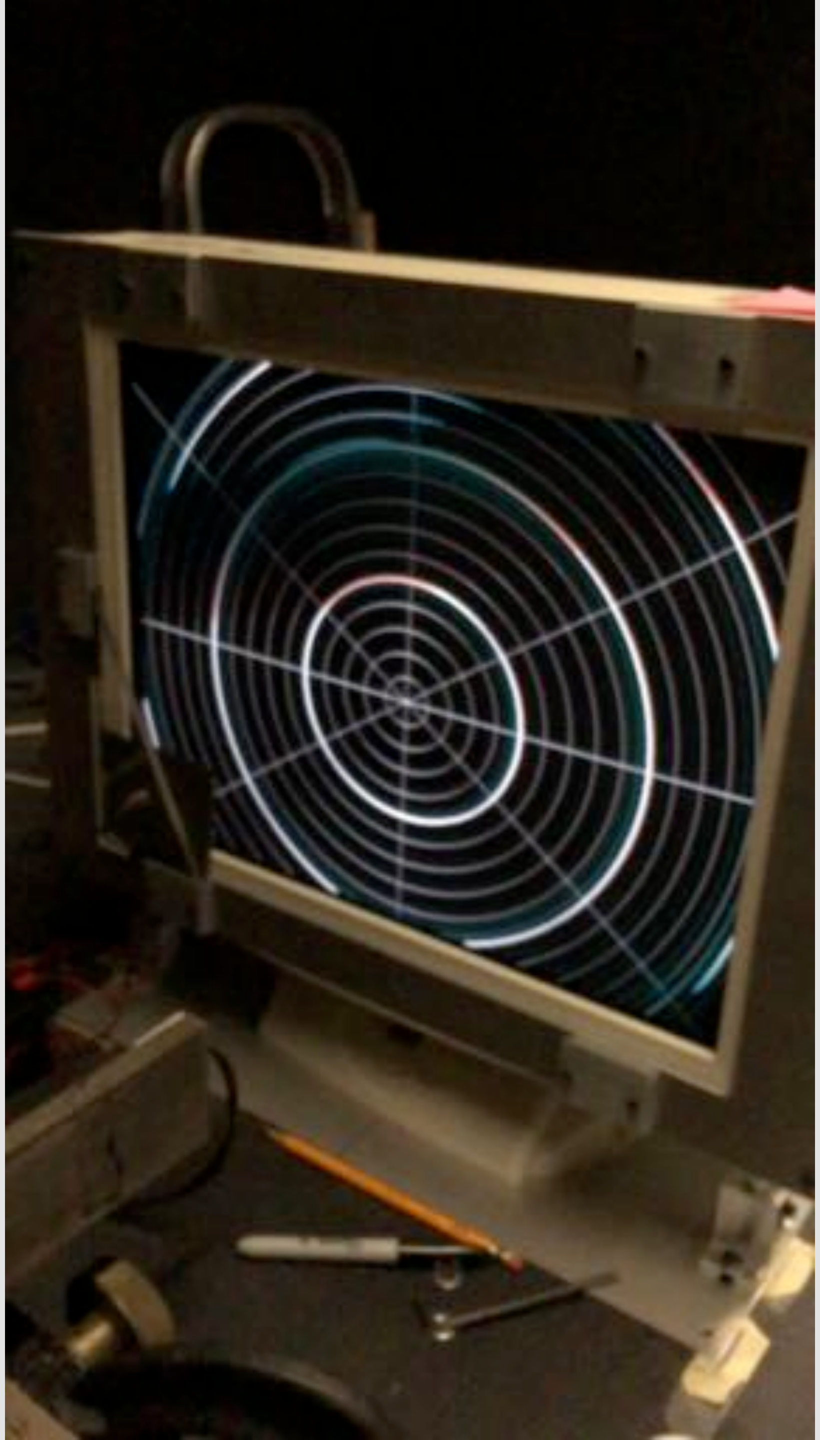
Love, G. D., Hoffman, D. M., Hands, P. J., Gao, J., Kirby, A. K., & Banks, M. S. (2009). High-speed switchable lens enables the development of a volumetric stereoscopic display. *Optics express*, *17*(18), 15716-15725.

Fixed view-point volumetric displays

- Images drawn on presentation planes at different focal distances
- Superimposition of multiple presentation planes additively on the retina
- Special treatment of scene points in between depth planes

Narain, R., Albert, R. A., Bulbul, A., Ward, G. J., Banks, M. S., & O'Brien, J. F. (2015). Optimal presentation of imagery with focus cues on multi-plane displays. *ACM Transactions on Graphics (TOG)*, *34*(4), 59.

Operation



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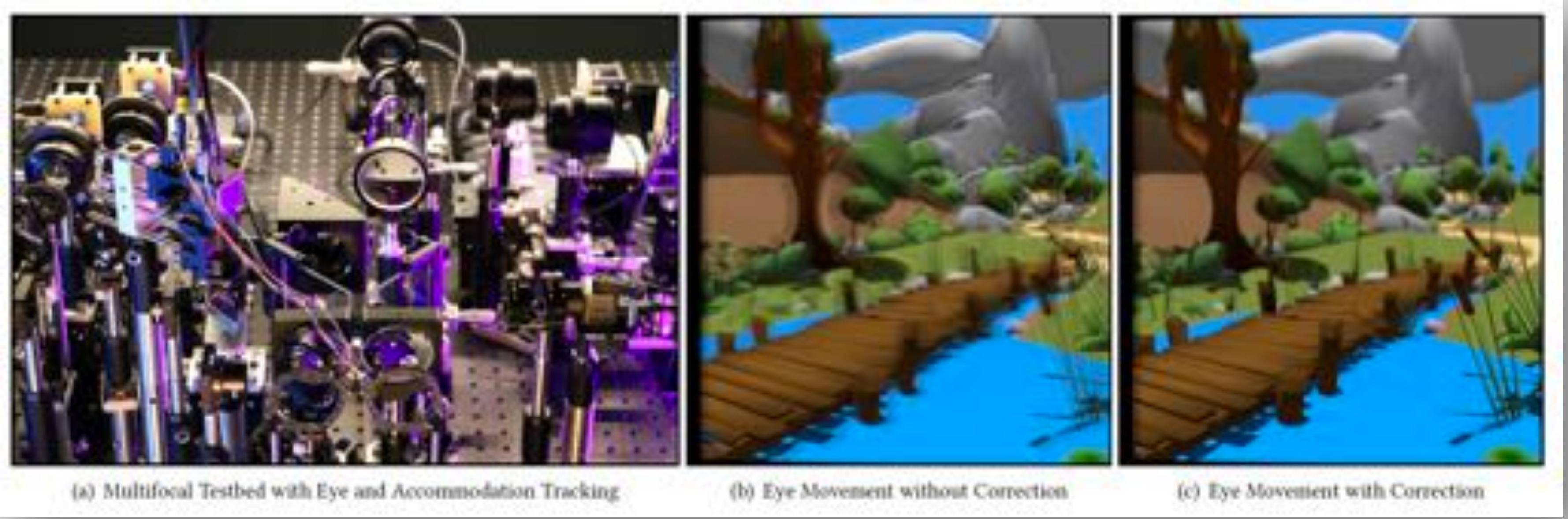
Advantages & disadvantages

- Very high resolution
- Accommodation cues
- Comfortable

- BUT

- Need to fixate head using bite-bars or other means

Fast gaze-contingent decomposition for multifocal displays



Mercier, O., Sulai, Y., Mackenzie, K., Zannoli, M., Hillis, J., Nowrouzezahrai, D., & Lanman, D. (2017). Fast gaze-contingent optimal decompositions for multifocal displays. *ACM Transactions on Graphics (TOG)*, *36*(6), 237.

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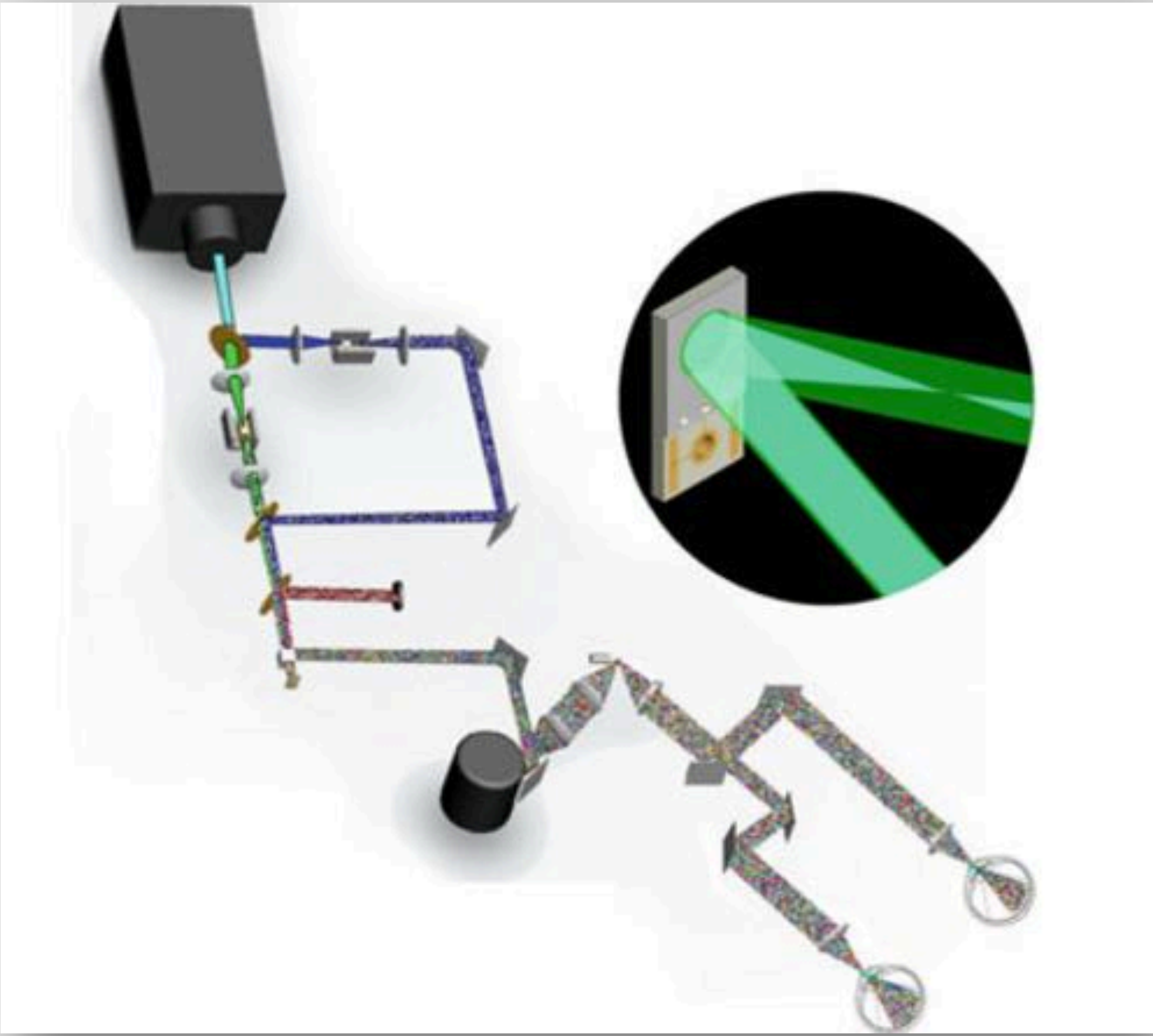
Multifocal scanned voxel displays



McQuaide, S. C., Seibel, E. J., Kelly, J. P., Schowengerdt, B. T., & Furness III, T. A. (2003). A retinal scanning display system that produces multiple focal planes with a deformable membrane mirror. *Displays*, *24*(2), 65-72.

Dual axis scanning mirror

Optotune

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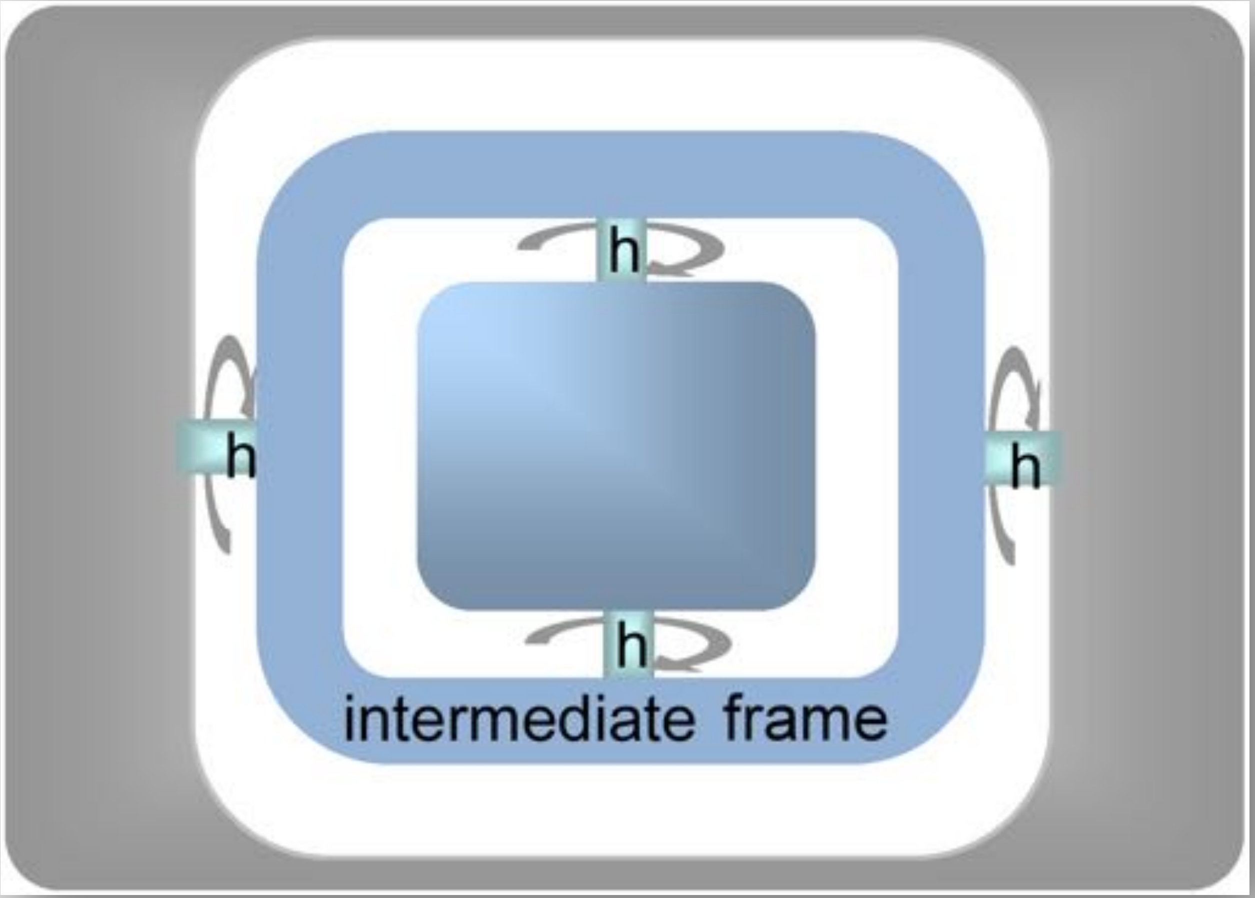
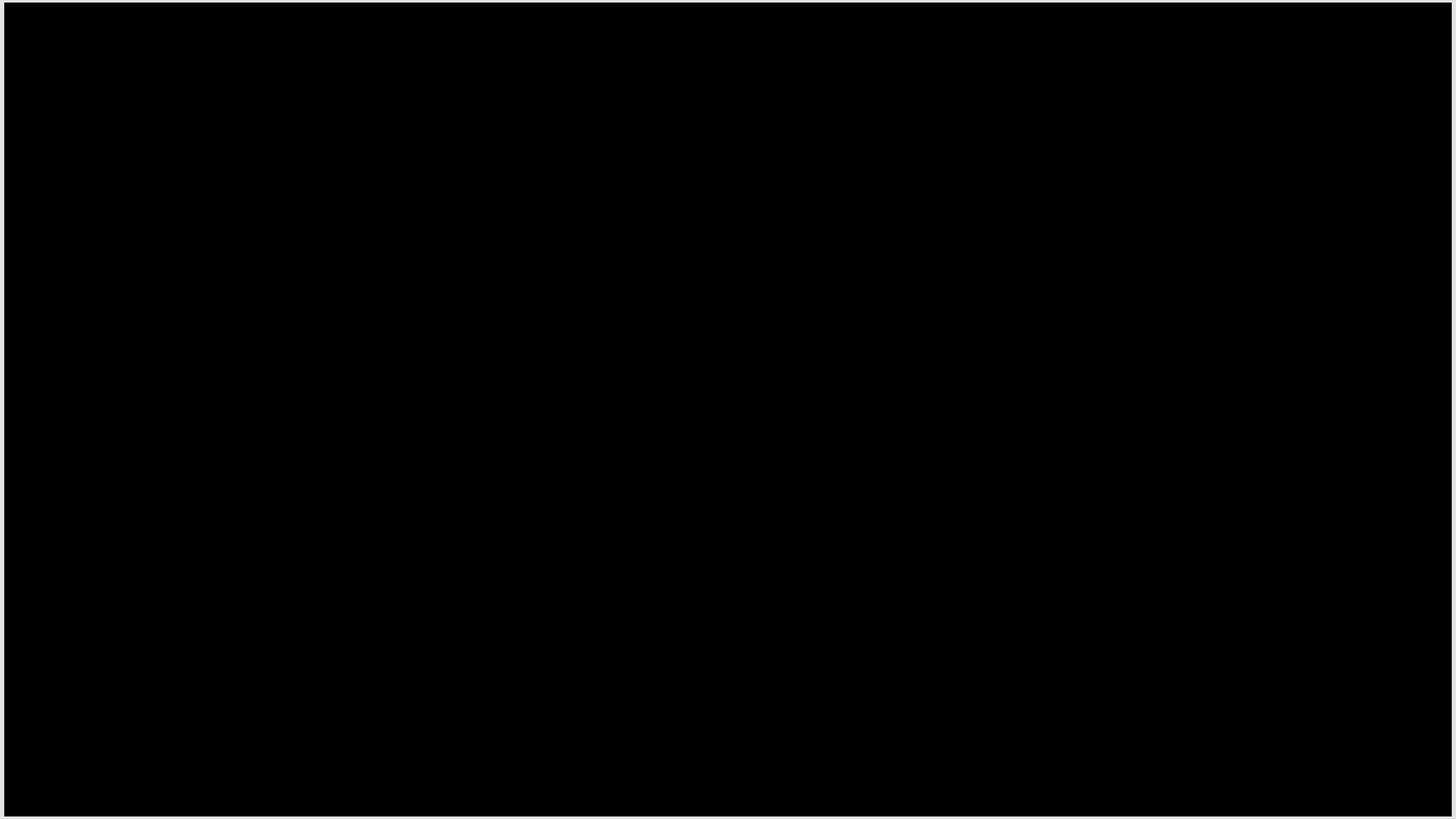
Principle of operation



Hainich & Bimber, 2017

Liquid lenses



Optotune

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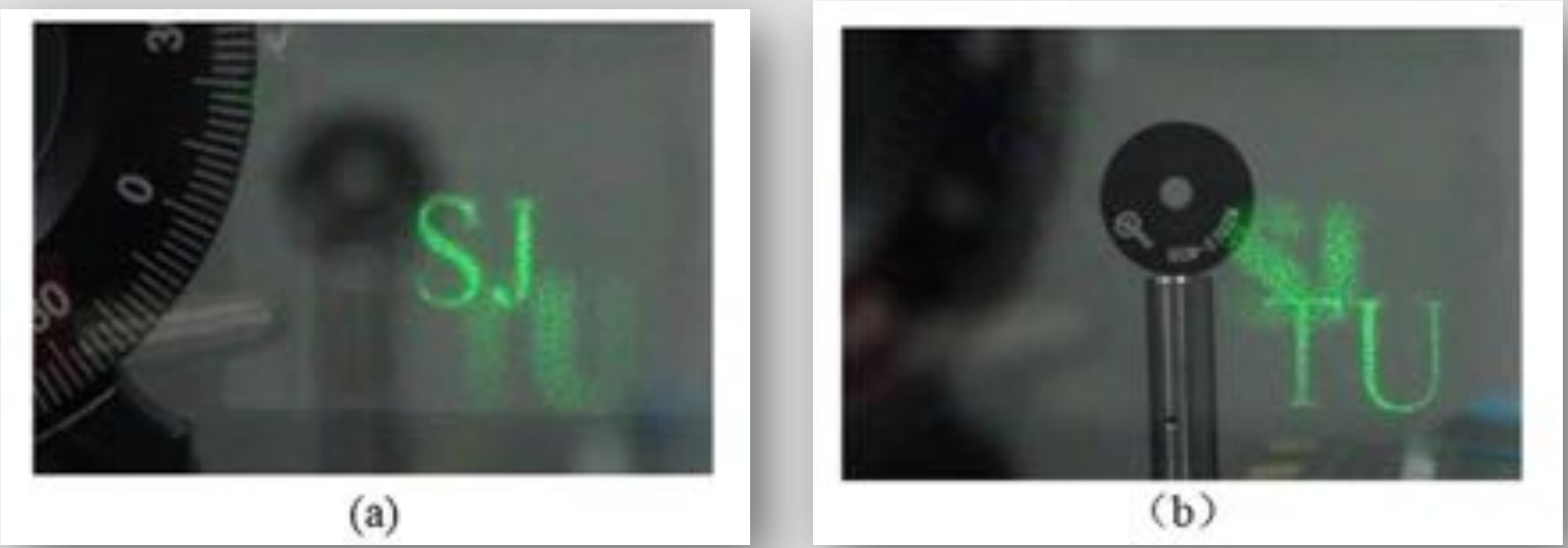
Focusing at different distances



(a) (b)

Xuan Wang

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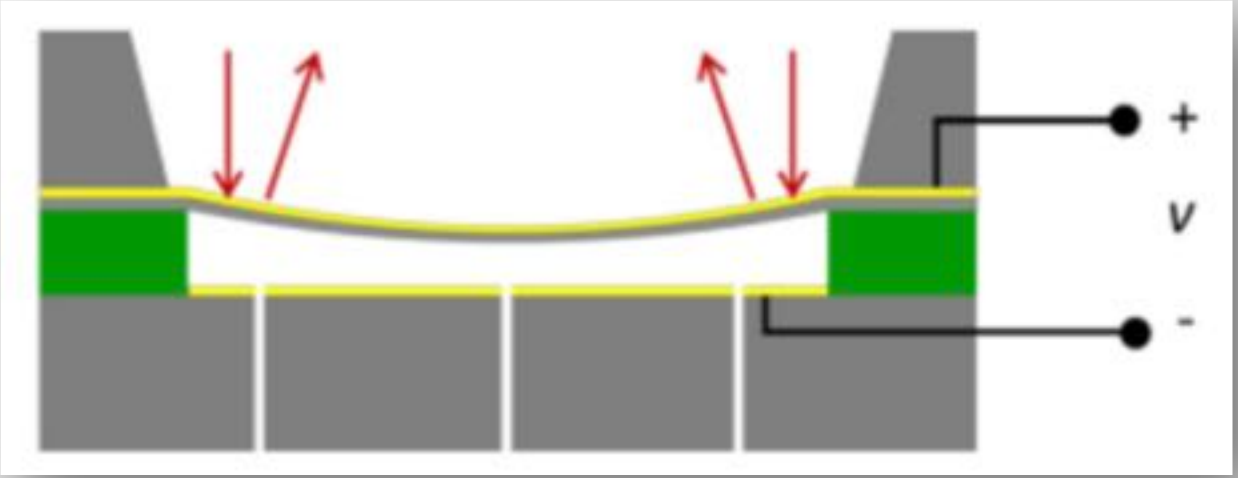
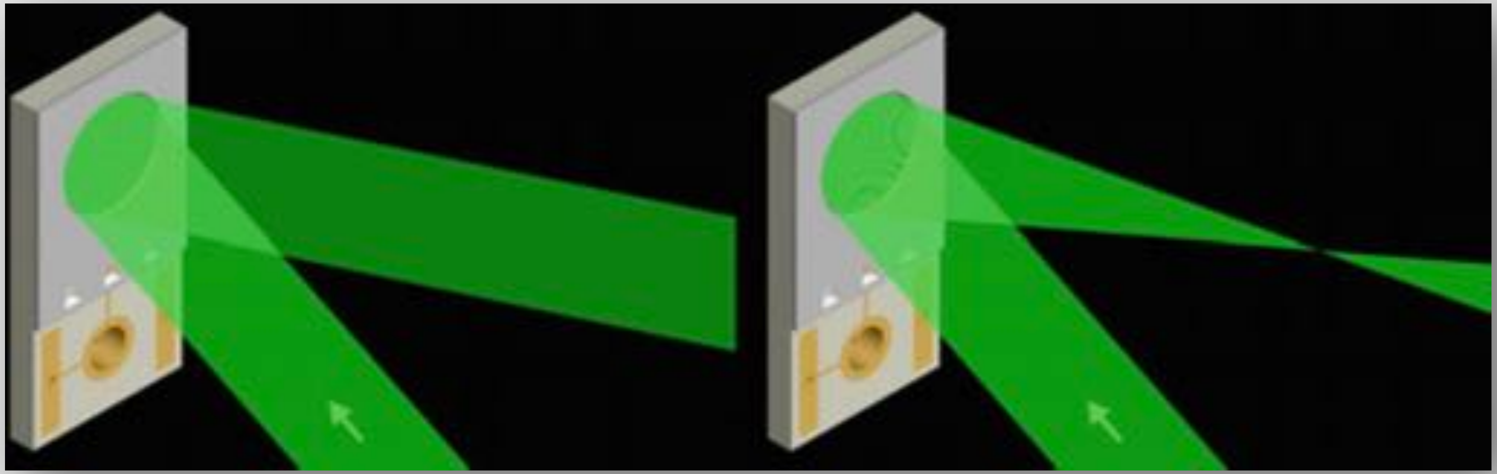
Deformable membrane mirrors





Schowengerdt & Seibel, 2012

McQuaide, S. C., Seibel, E. J., Kelly, J. P., Schowengerdt, B. T., & Furness III, T. A. (2003). A retinal scanning display system that produces multiple focal planes with a deformable membrane mirror. *Displays*, *24*(2), 65-72.

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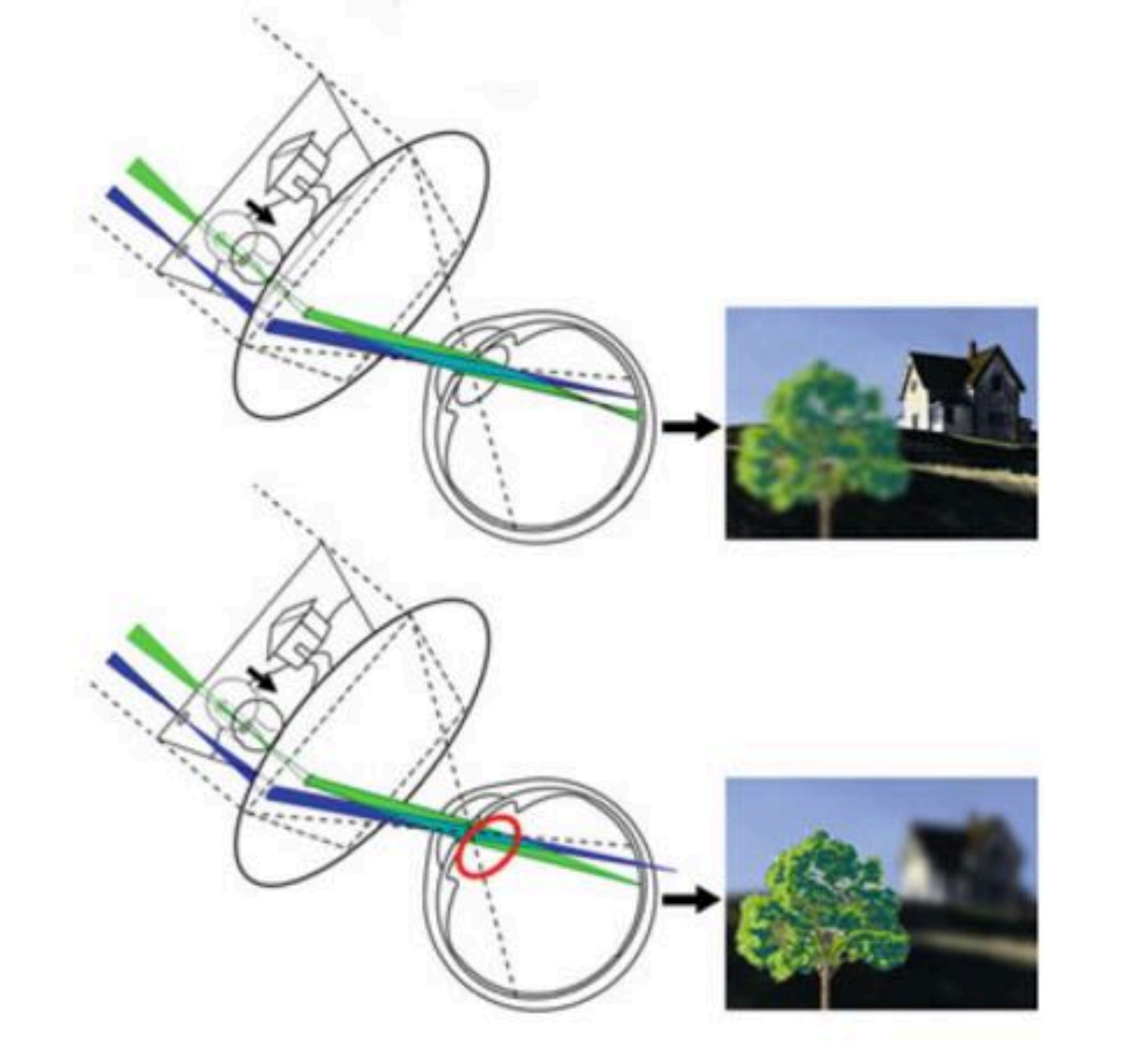
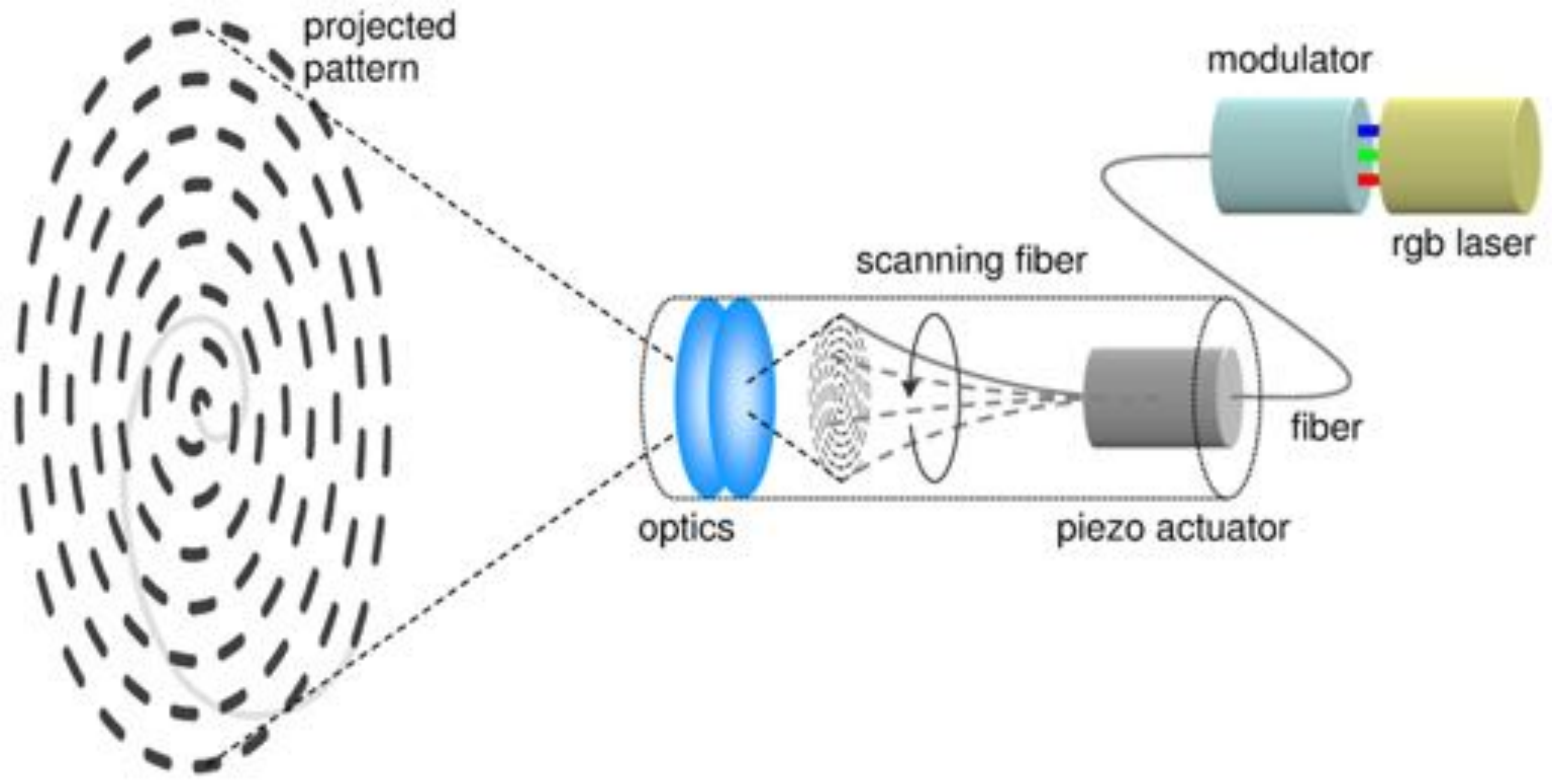
Multifocal scanned voxel displays

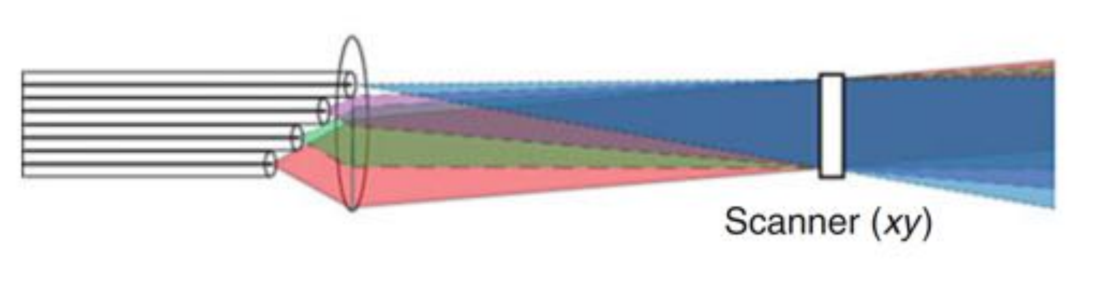


McQuaide, S. C., Seibel, E. J., Kelly, J. P., Schowengerdt, B. T., & Furness III, T. A. (2003). A retinal scanning display system that produces multiple focal planes with a deformable membrane mirror. *Displays*, *24*(2), 65-72.

Scanning fiber projector



Hainich & Bimber, 2017



Schowengerdt & Seibel, 2012

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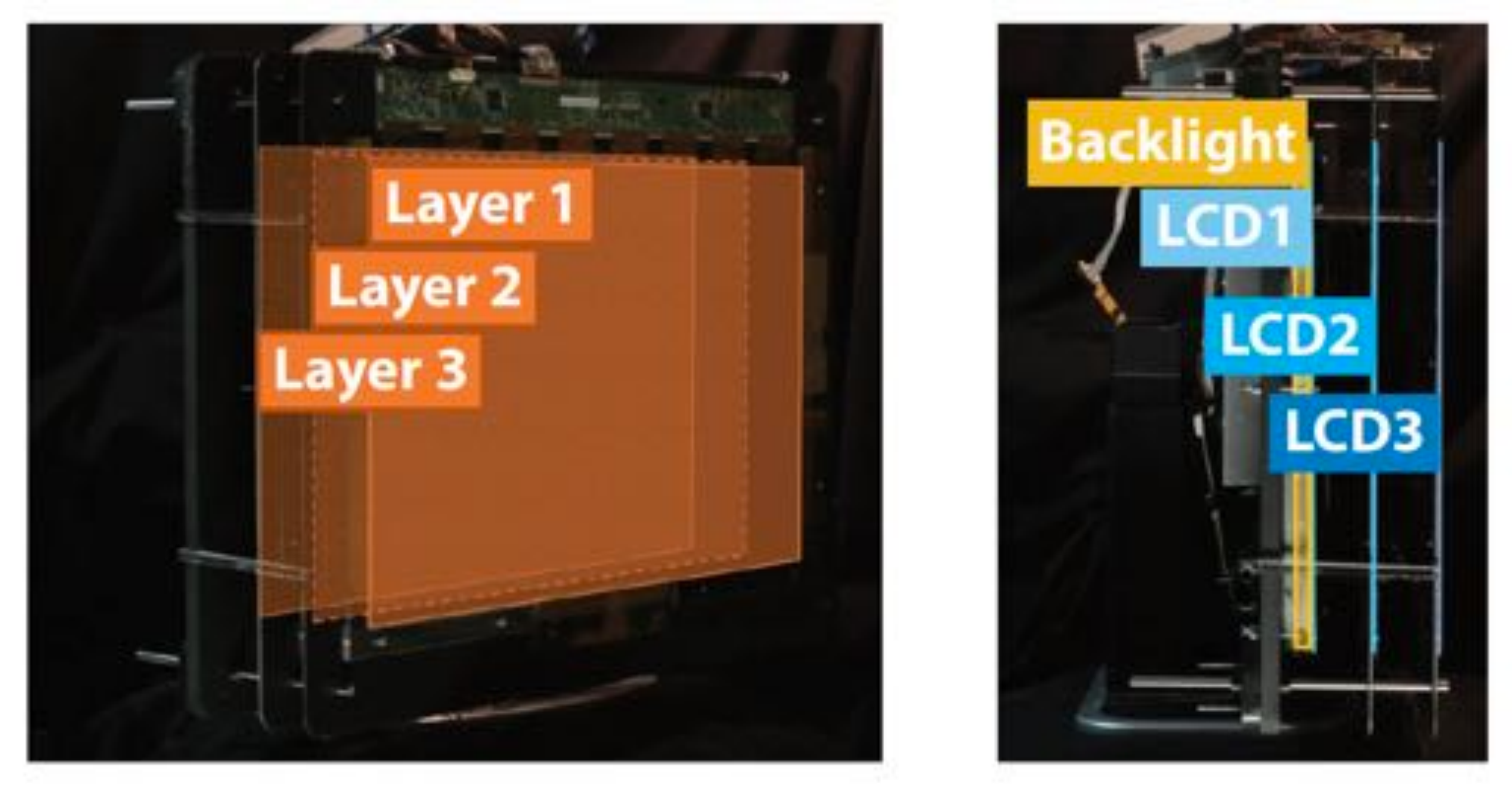
Light field displays

- Emit a 4-dimensional distribution of light rays
  - 2D on the display
  - Another 2D horizontal & vertical angle of each pixel
- Each light ray carries radiance at some location into a specific direction

Lanman, D., Hirsch, M., Kim, Y., & Raskar, R. (2010, December). Content-adaptive parallax barriers: optimizing dual-layer 3D displays using low-rank light field factorization. In *ACM Transactions on Graphics (TOG)* (Vol. 29, No. 6, p. 163). ACM.

Light field displays



Wetzstein, G., Lanman, D., Hirsch, M., & Raskar, R. (2012). Tensor displays: compressive light field synthesis using multilayer displays with directional backlighting.

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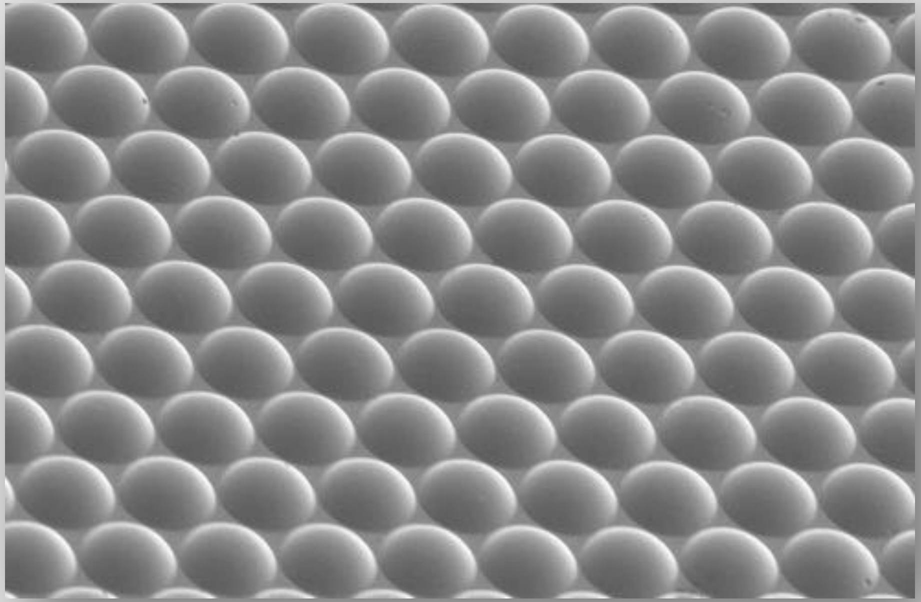
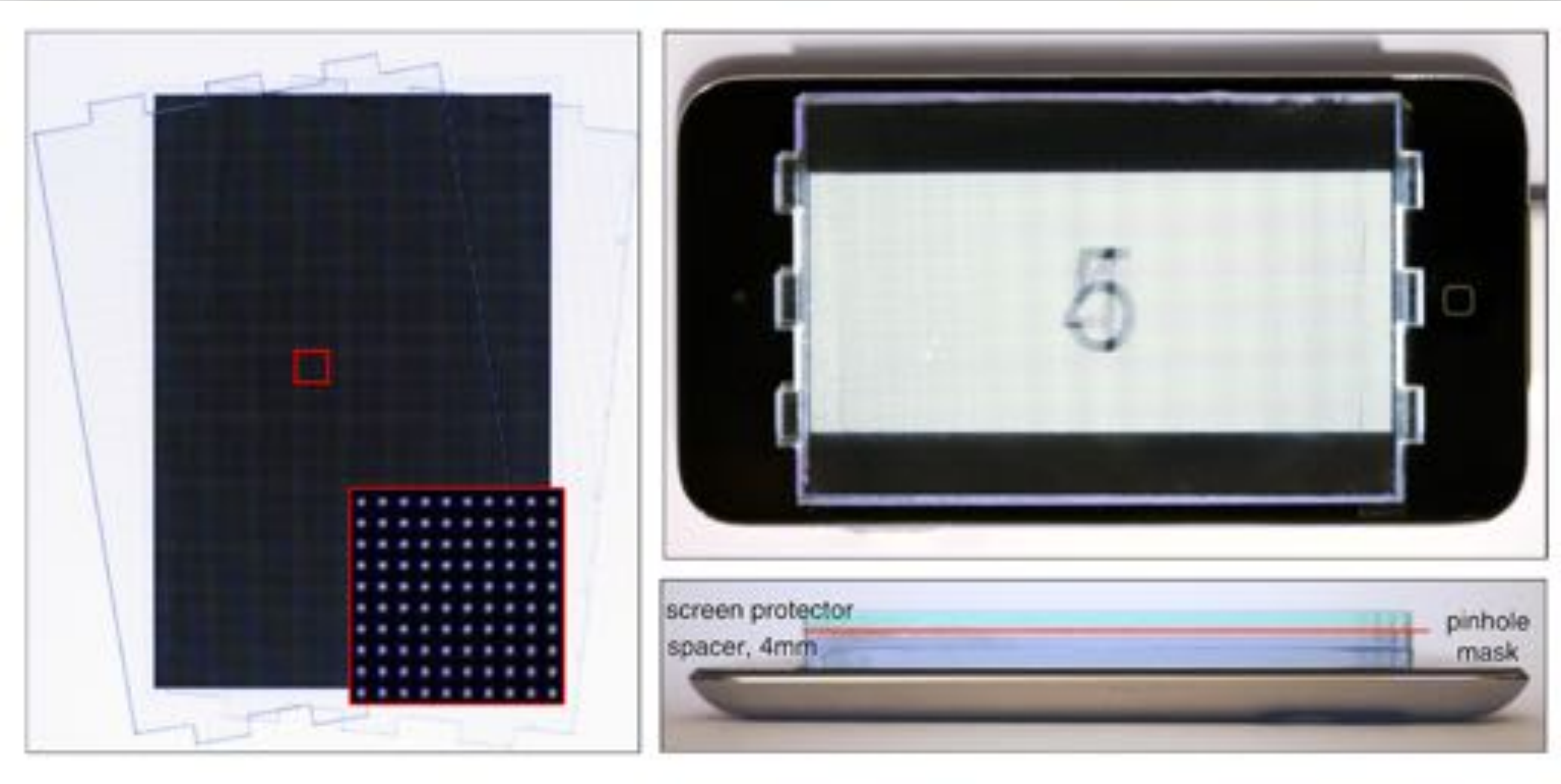
Example construction

- Sandwich a microlens array between an LCD-pair stack
- Perform light beam steering and modulation



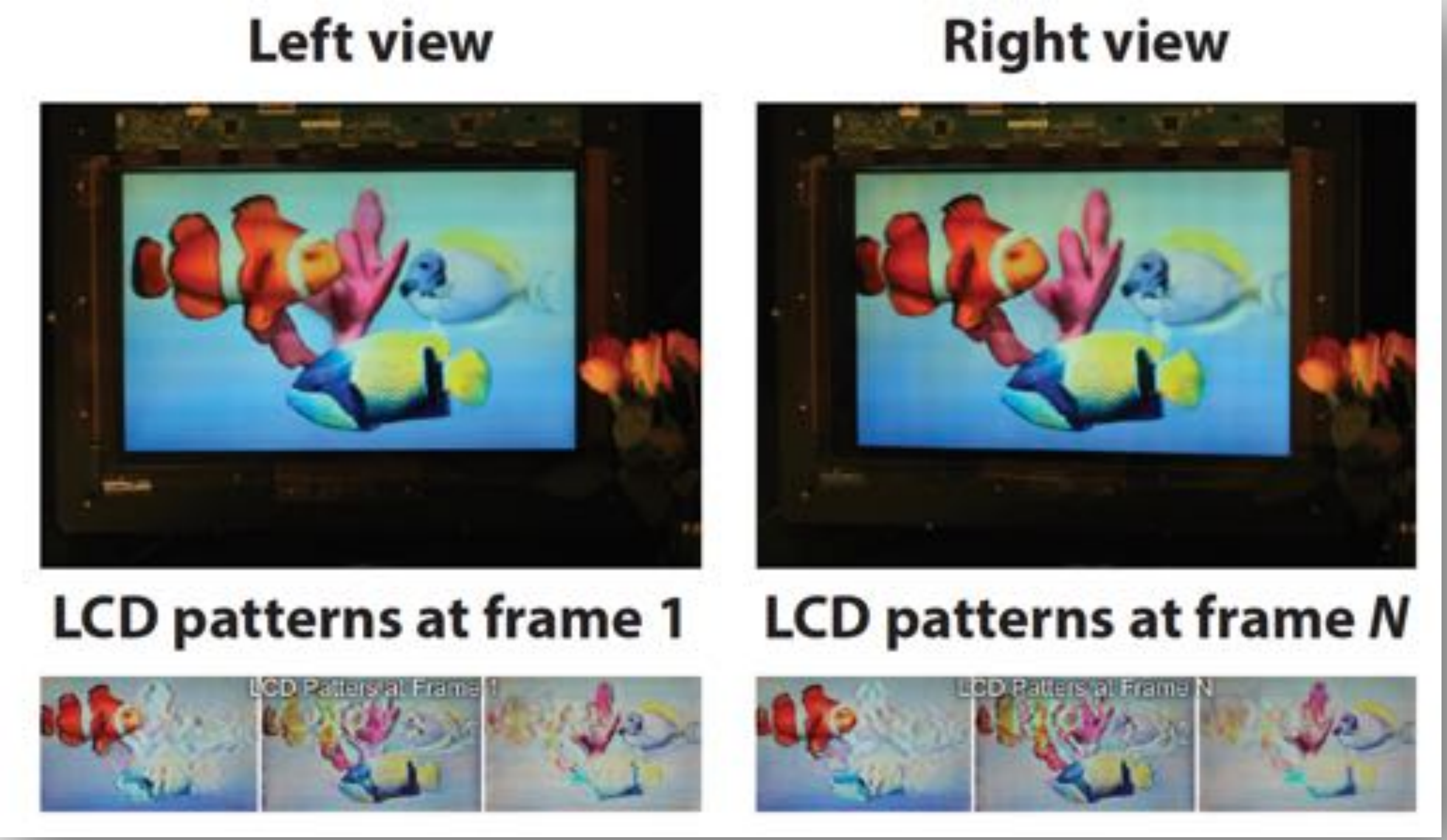
Planettech International

Pinhole parallax barrier
5x5 pixels under each pinhole



Huang, F. C., Wetzstein, G., Barsky, B. A., & Raskar, R. (2014). Eyeglasses-free display: towards correcting visual aberrations with computational light field displays. *ACM Transactions on Graphics (TOG)*, *33*(4), 59.

Light field displays



Wetzstein, G., Lanman, D., Hirsch, M., & Raskar, R. (2012). Tensor displays: compressive light field synthesis using multilayer displays with directional backlighting.

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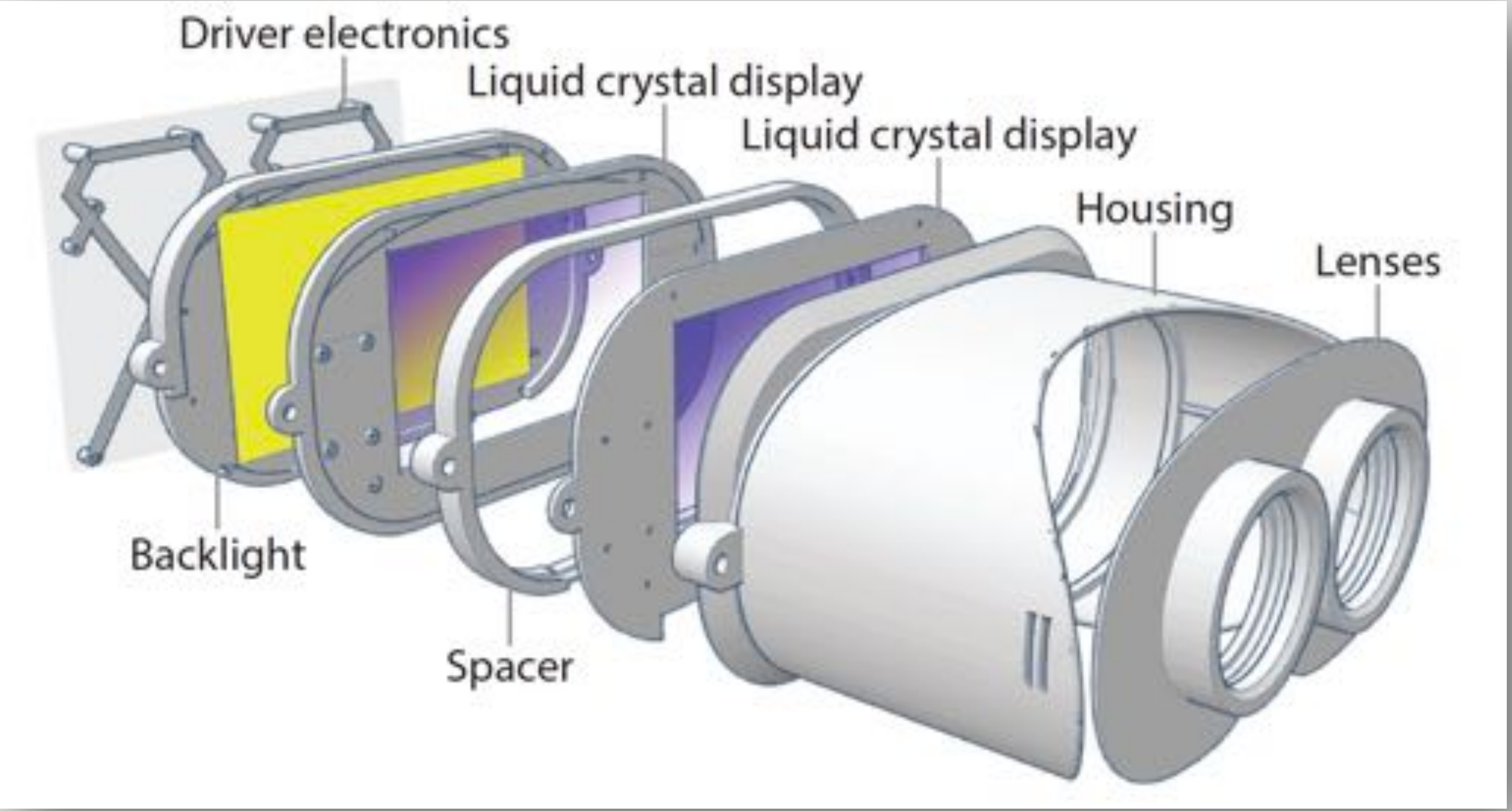
Wearable light field displays



Huang et al., 2015

Lanman, D., & Luebke, D. (2013). Near-eye light field displays. *ACM Transactions on Graphics (TOG)*, *32*(6), 220.

Huang, F. C., Chen, K., & Wetzstein, G. (2015). The light field stereoscope: immersive computer graphics via factored near-eye light field displays with focus cues. *ACM Transactions on Graphics (TOG)*, *34*(4), 60.

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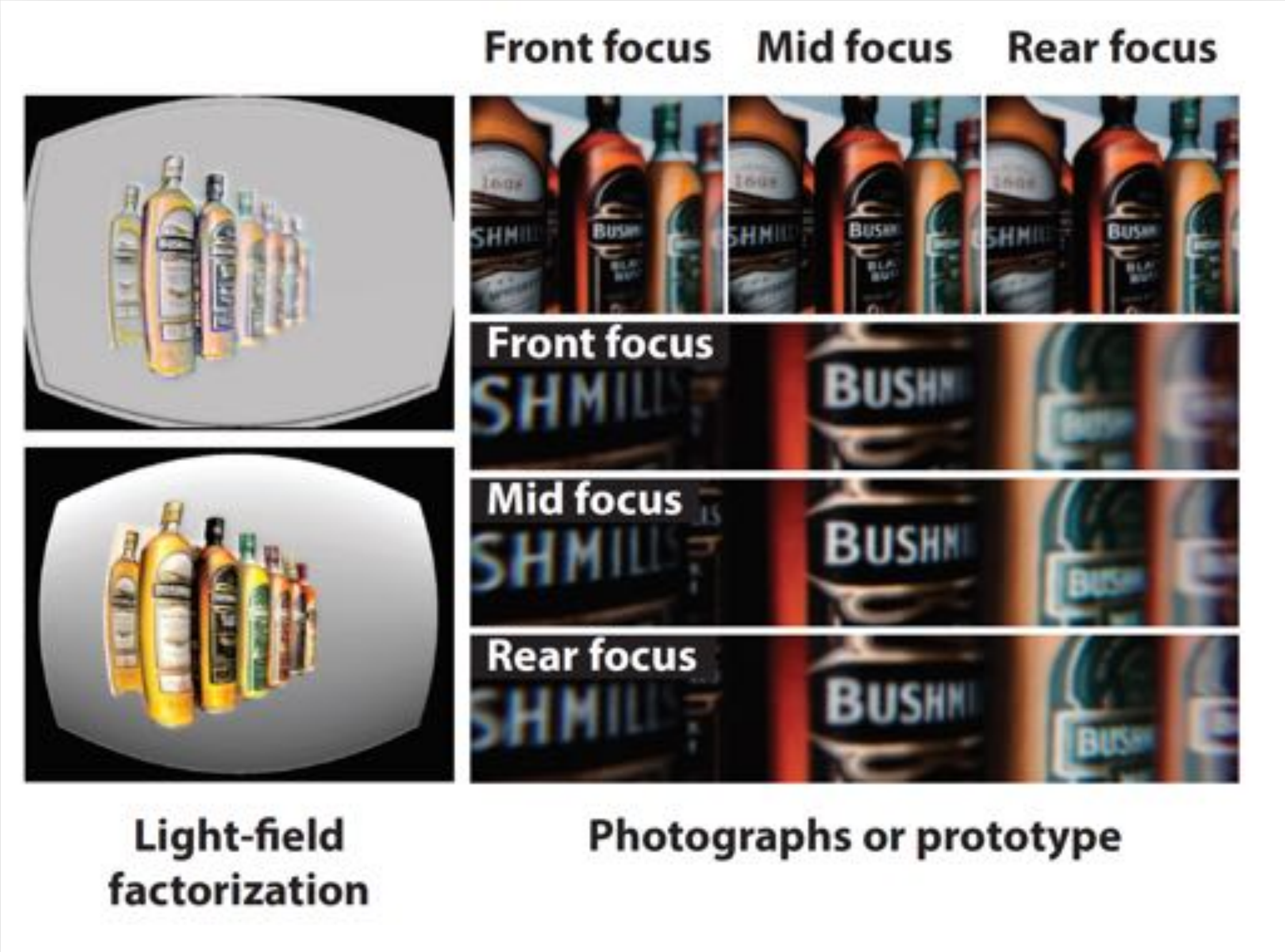
Wearable light field displays



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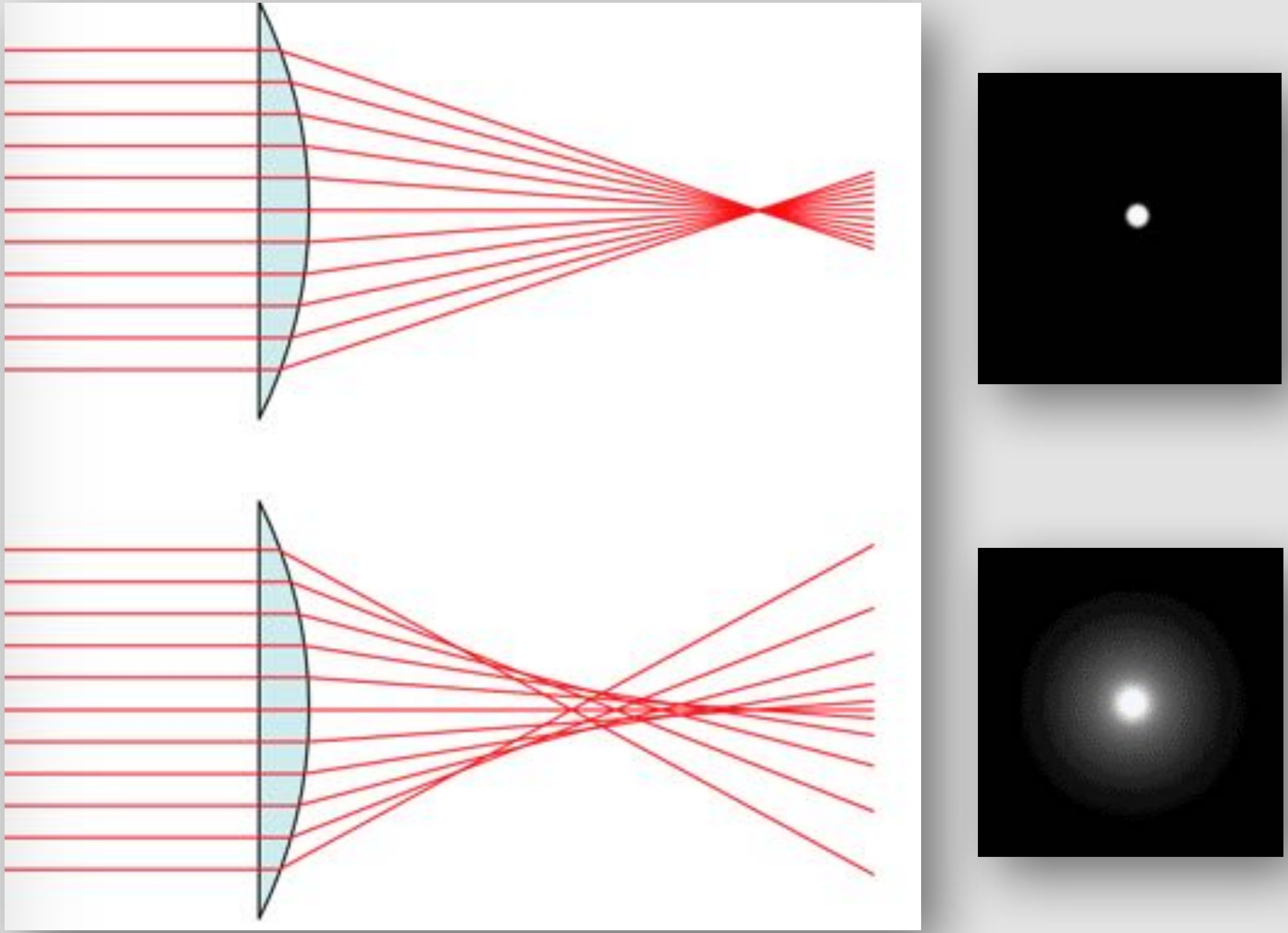
Spherical aberrations



Mglg

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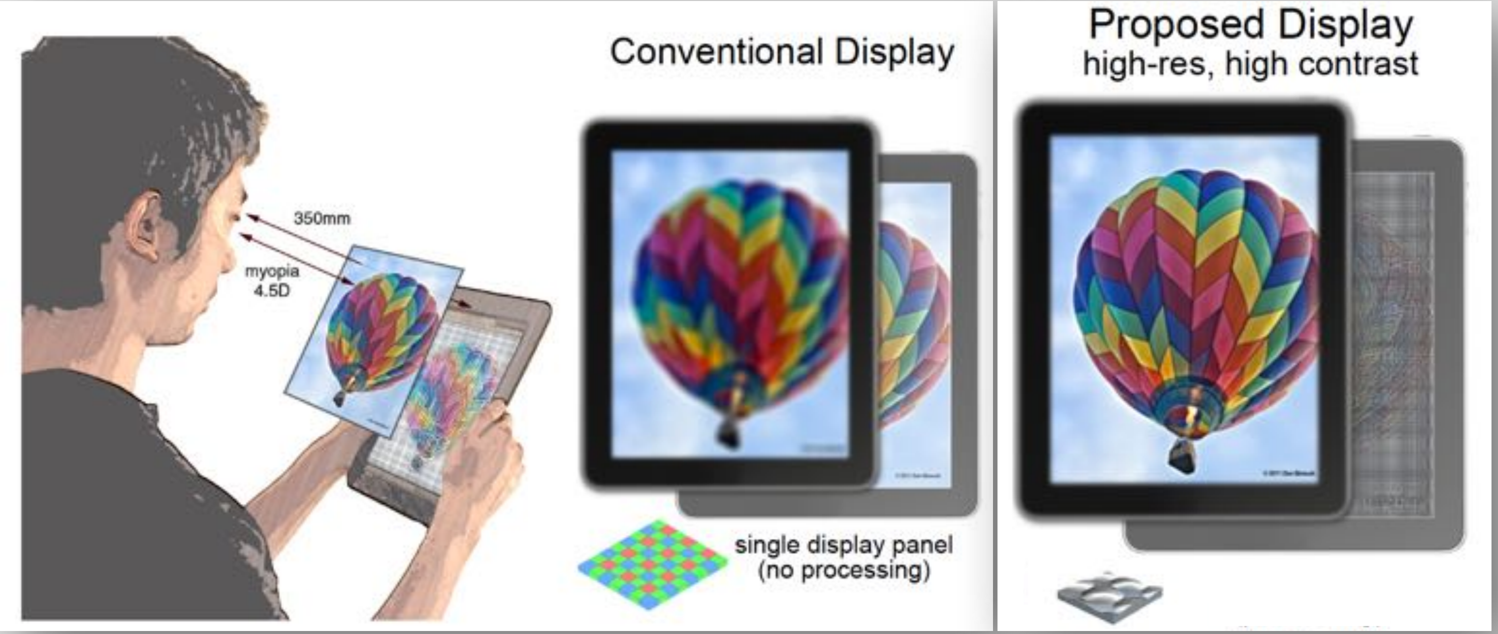
Pre-correcting aberrations with light field displays



Huang, F. C., Wetzstein, G., Barsky, B. A., & Raskar, R. (2014). Eyeglasses-free display: towards correcting visual aberrations with computational light field displays. *ACM Transactions on Graphics (TOG)*, *33*(4), 59.

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Holography

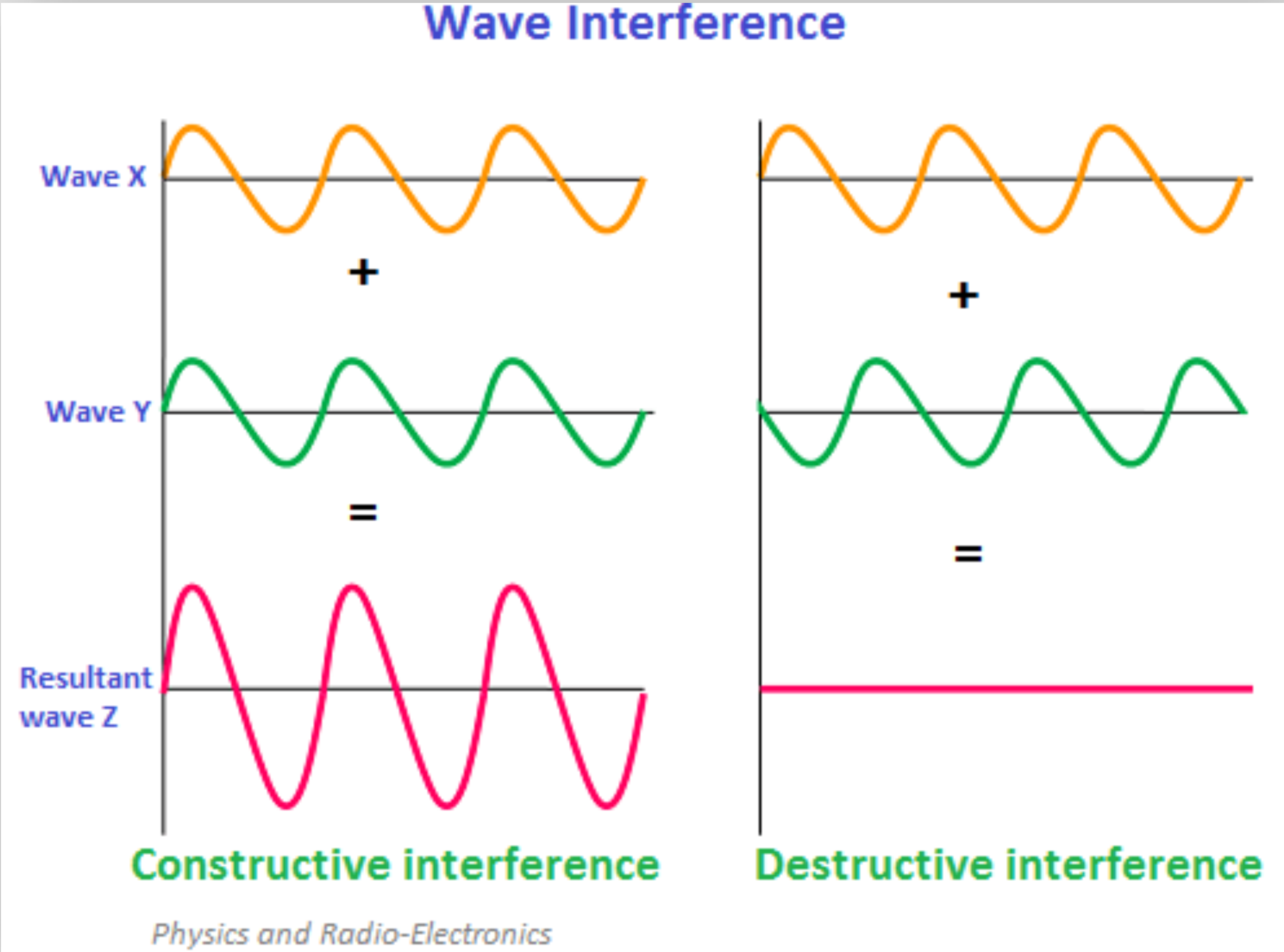
- The ultimate 3D image generation technique
- Exact wave-front reconstruction
- Holograms record and play all characteristics of light waves
  - phase, amplitude, wavelength

Holography

- Ideally no difference between real object and its hologram
- Recorded using lasers that exhibit coherent monochrome light with regular wave-fronts on photographic plates
- Can use 3 colored lasers for color reproduction
- Computer generated holograms very promising in the -far- future

Principles

- Interference



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Principles

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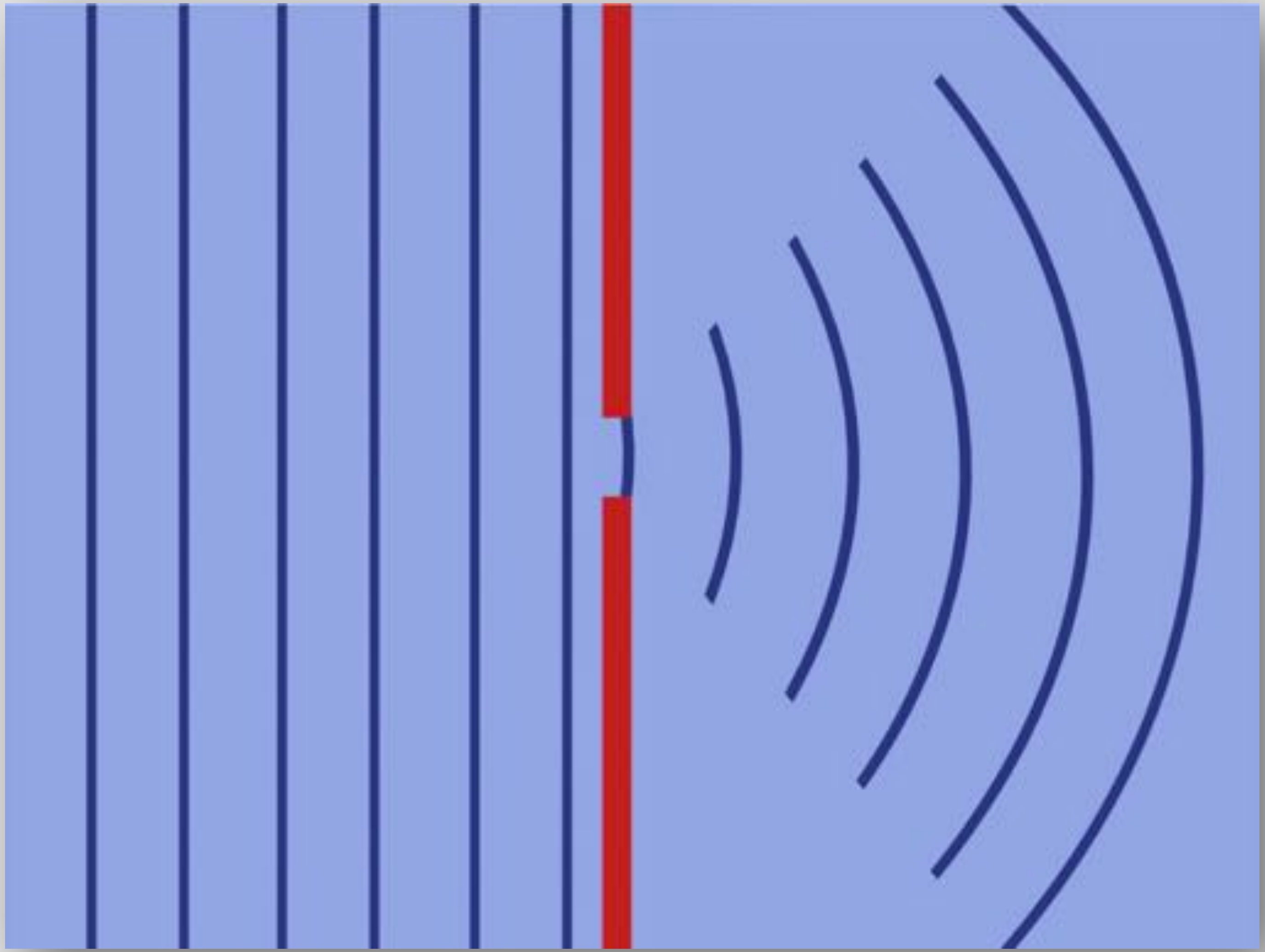
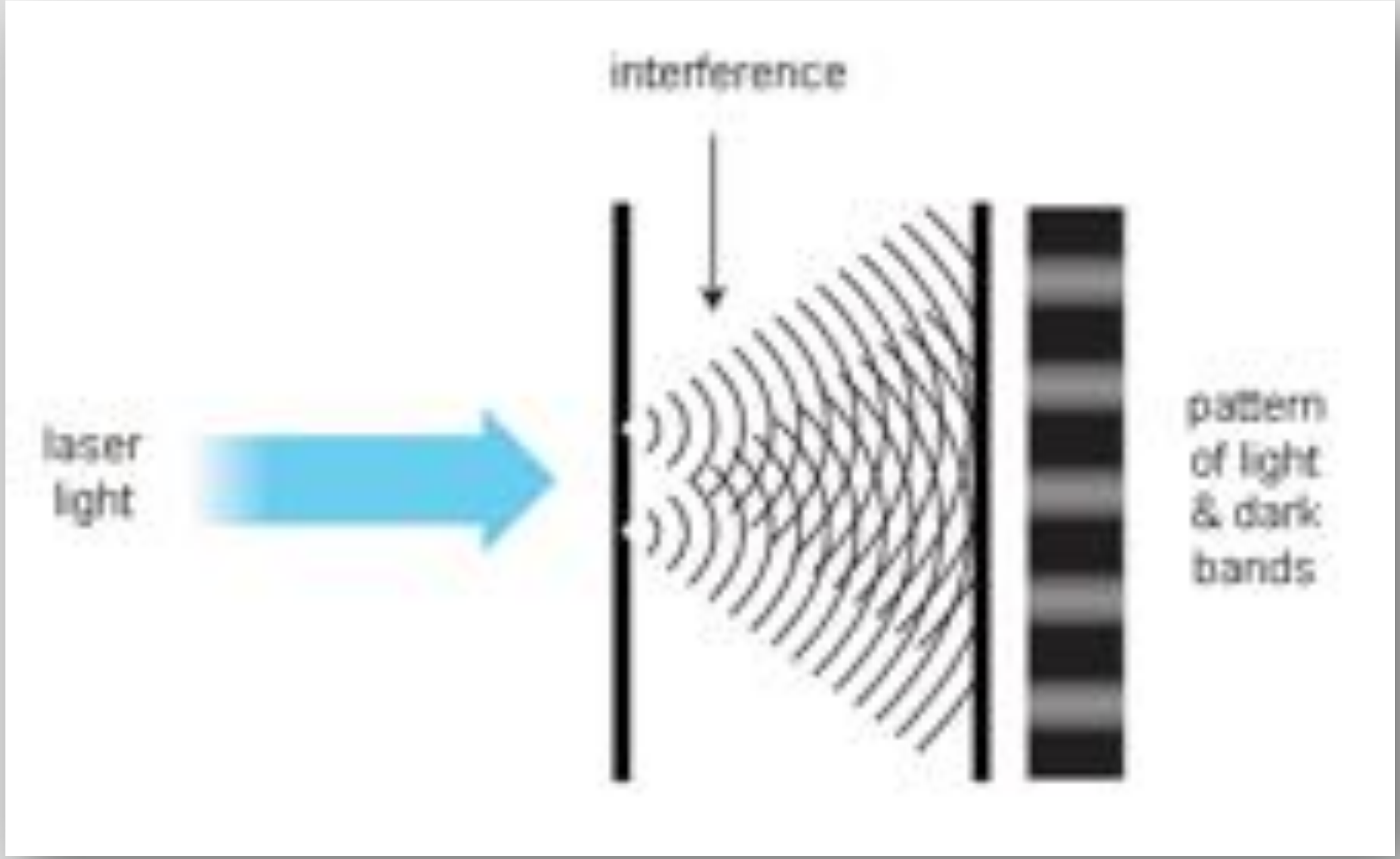
- Interference
- Diffraction

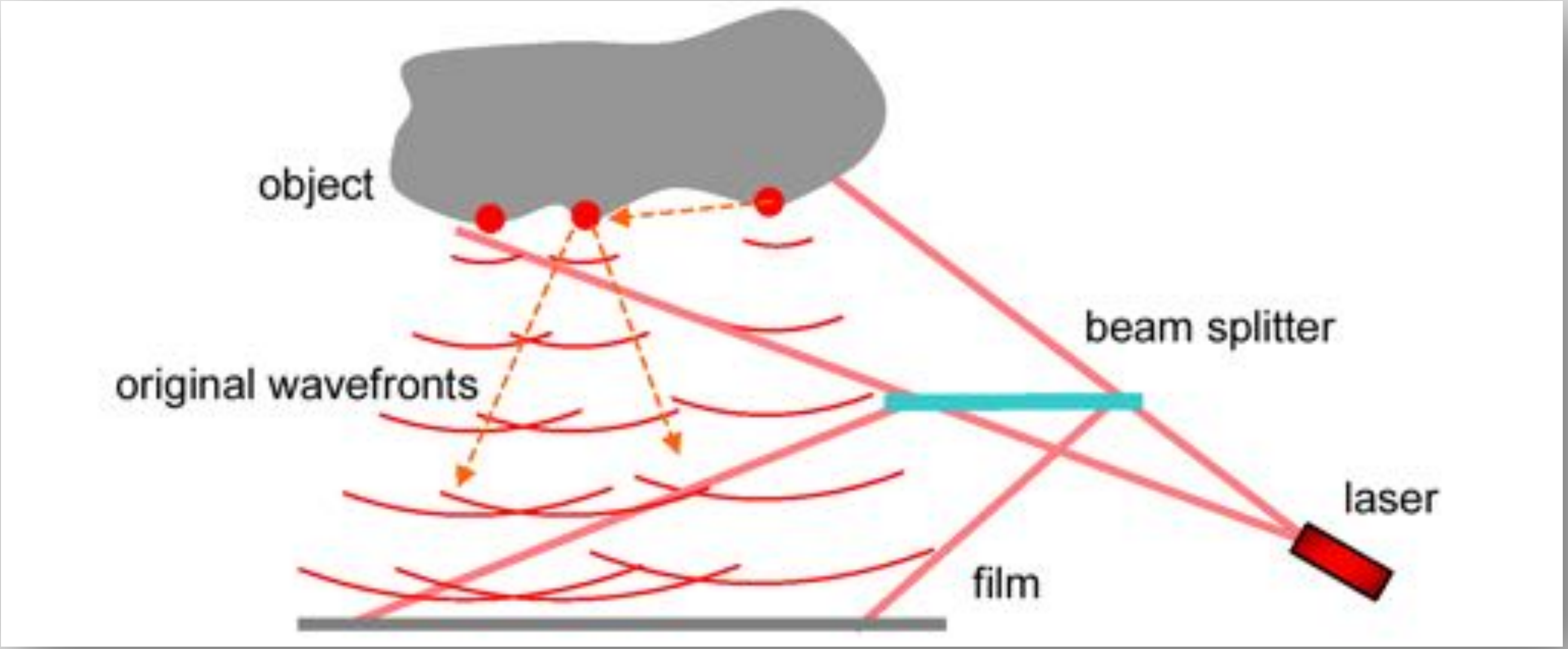


Principles

- Interference
- Diffraction
- Fringe pattern superposition



Recording holograms



Hainich & Bimber, 2017

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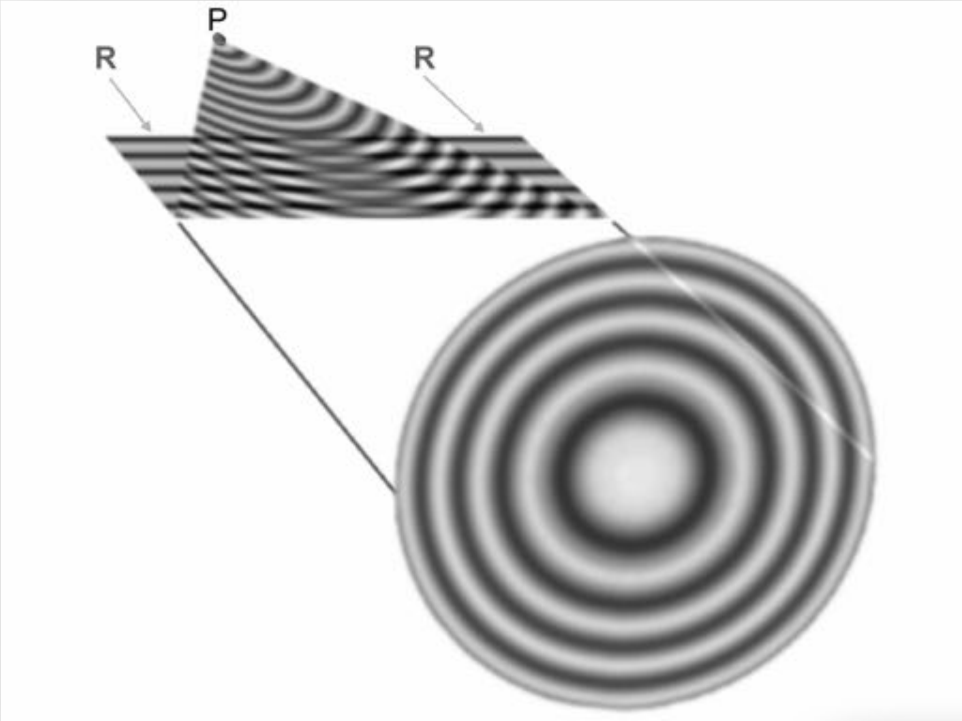
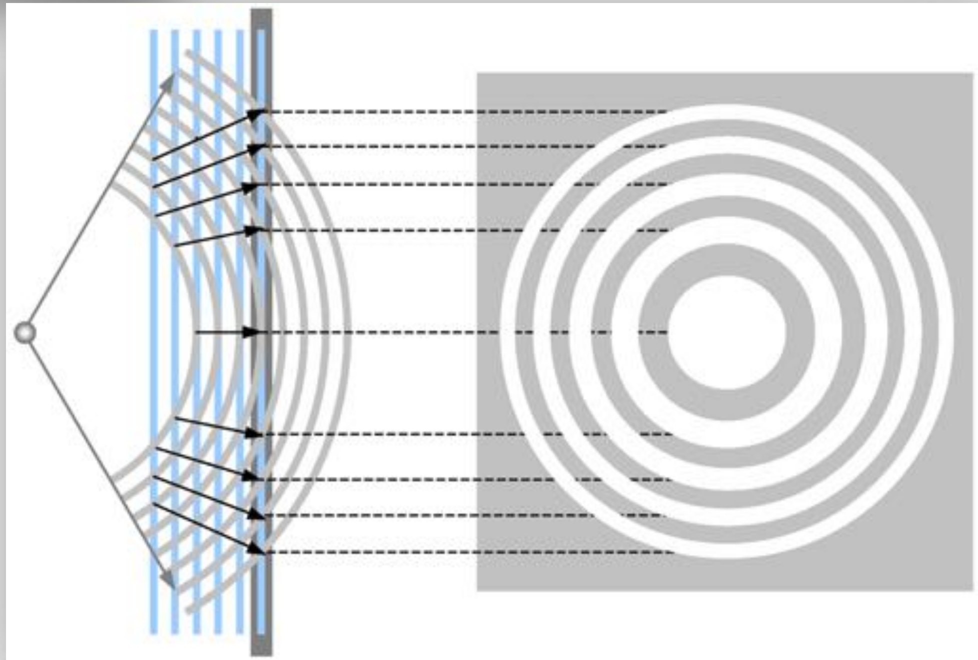
Recorded fringe patterns



Hainich & Bimber, 2017



Hainich & Bimber, 2017

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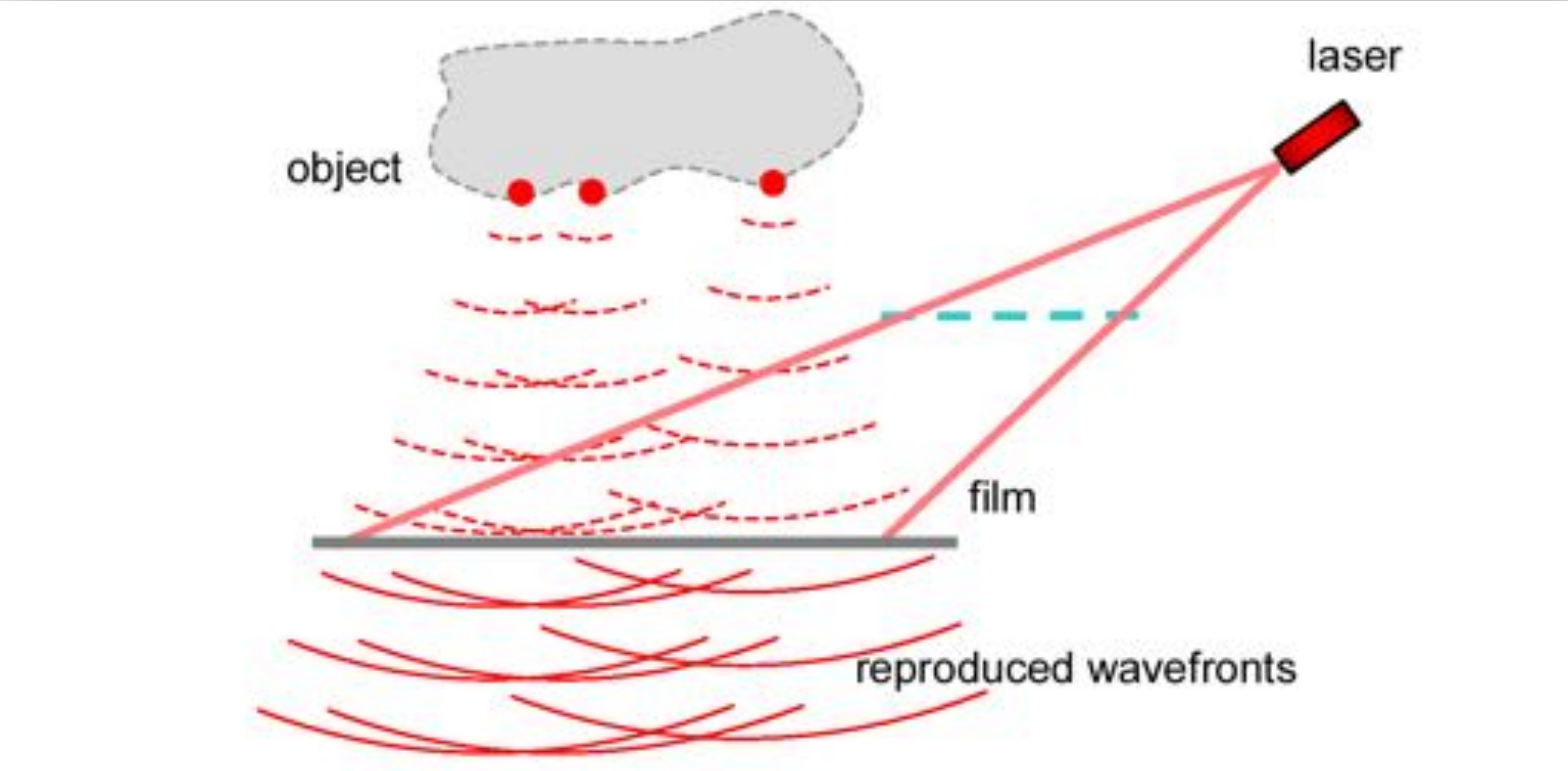
Playing-back holograms



Hainich & Bimber, 2017

Computer generated holograms

- Computer generated fringe patterns
- Use Spatial Light Modulators (SLMs) for display
- DMDs and F-LCDs often used

Holographic near-eye displays

Maimone, A., Georgiou, A., & Kollin, J. S. (2017). Holographic near-eye displays for virtual and augmented reality. *ACM Transactions on Graphics (TOG)*, *36*(4), 85.

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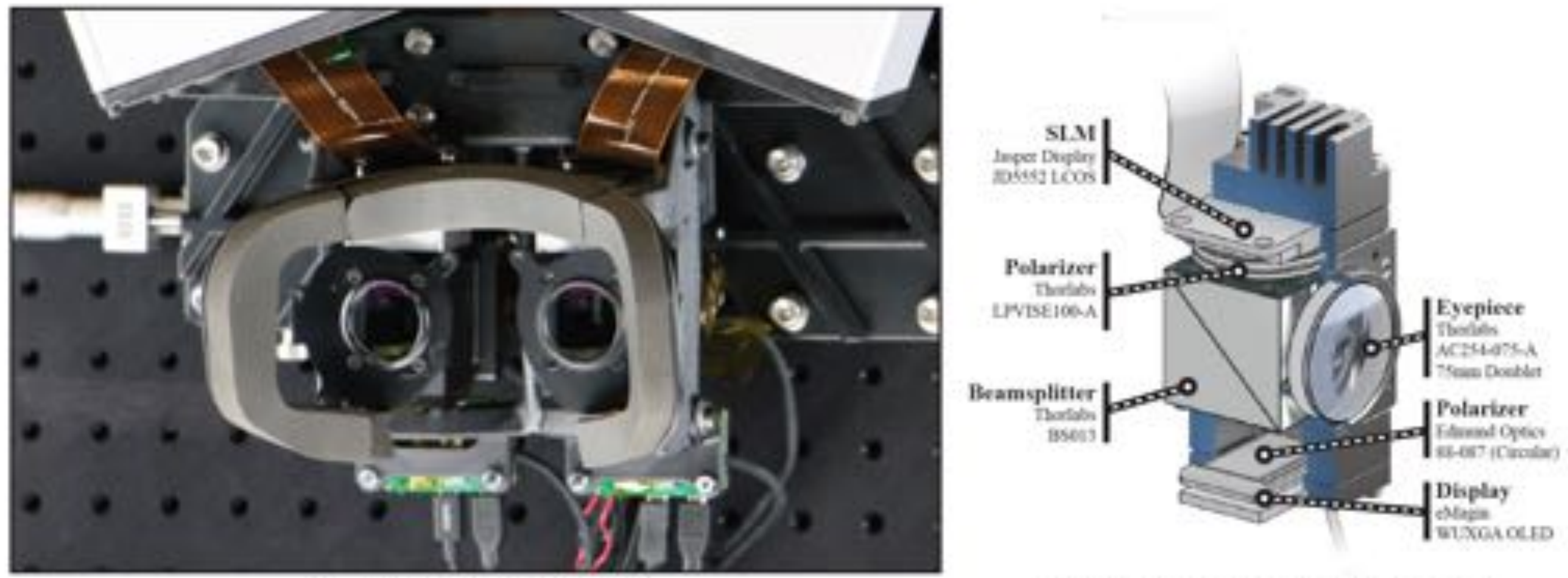
Focal surface displays

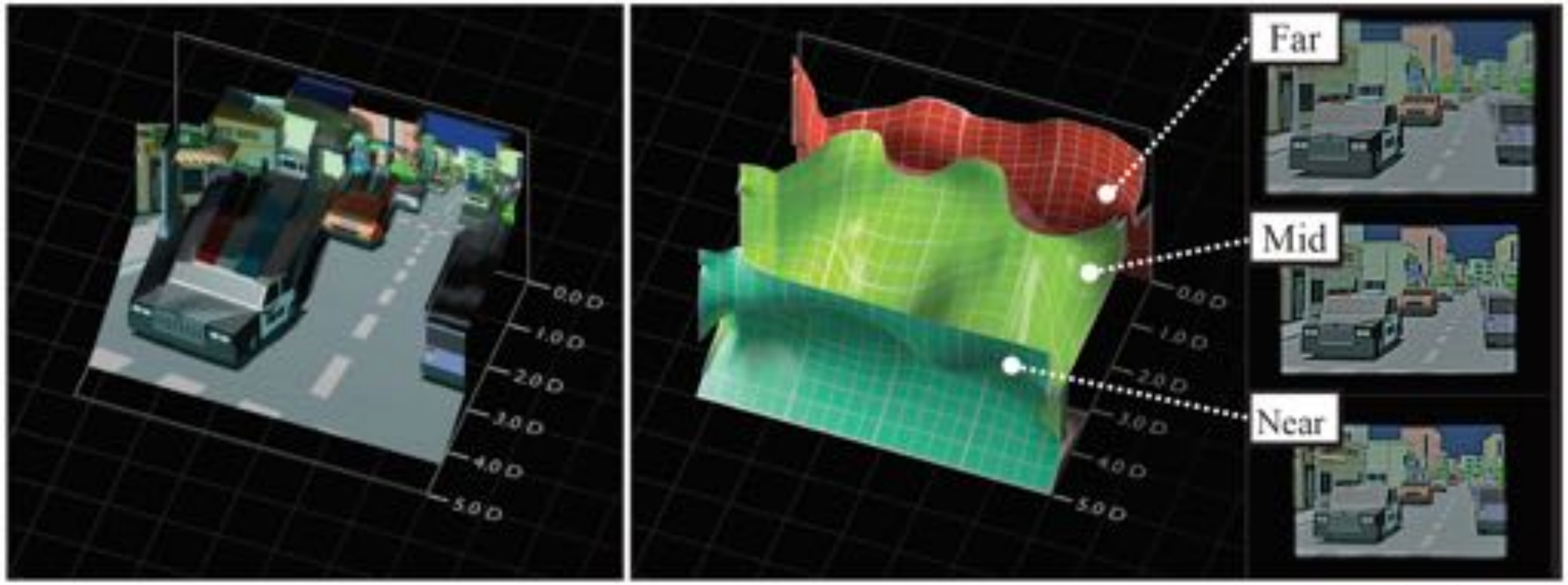


(a) Construction of the Prototype

(b) Arrangement of the Optical Components

Matsuda, N., Fix, A., & Lanman, D. (2017). Focal surface displays. *ACM Transactions on Graphics (TOG)*, *36*(4), 86.

Focal surface displays



Target Scene

Focal Surface and Color Decomposition

Matsuda, N., Fix, A., & Lanman, D. (2017). Focal surface displays. *ACM Transactions on Graphics (TOG)*, *36*(4), 86.

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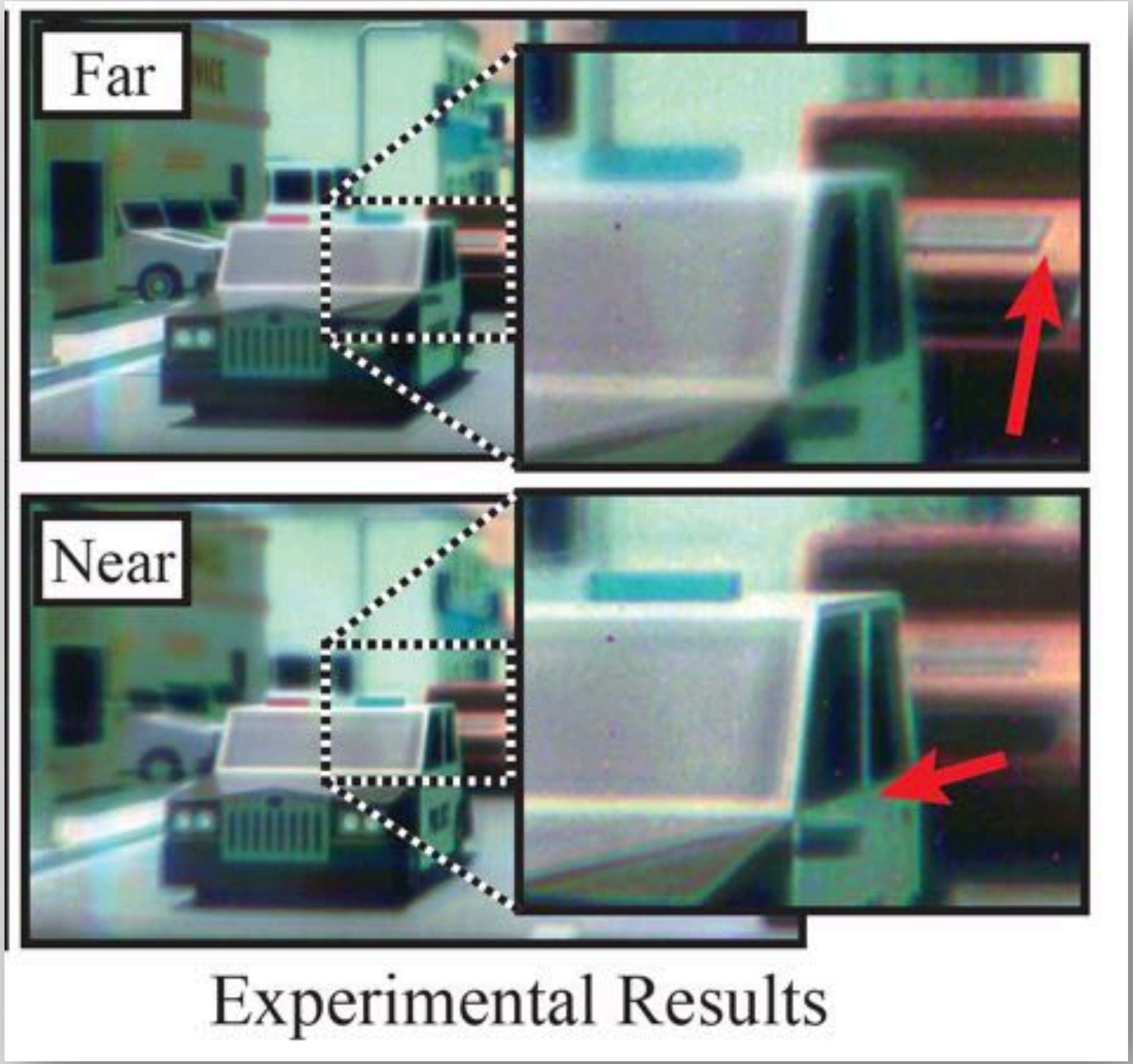
Focal surface displays



Matsuda, N., Fix, A., & Lanman, D. (2017). Focal surface displays. *ACM Transactions on Graphics (TOG)*, *36*(4), 86.

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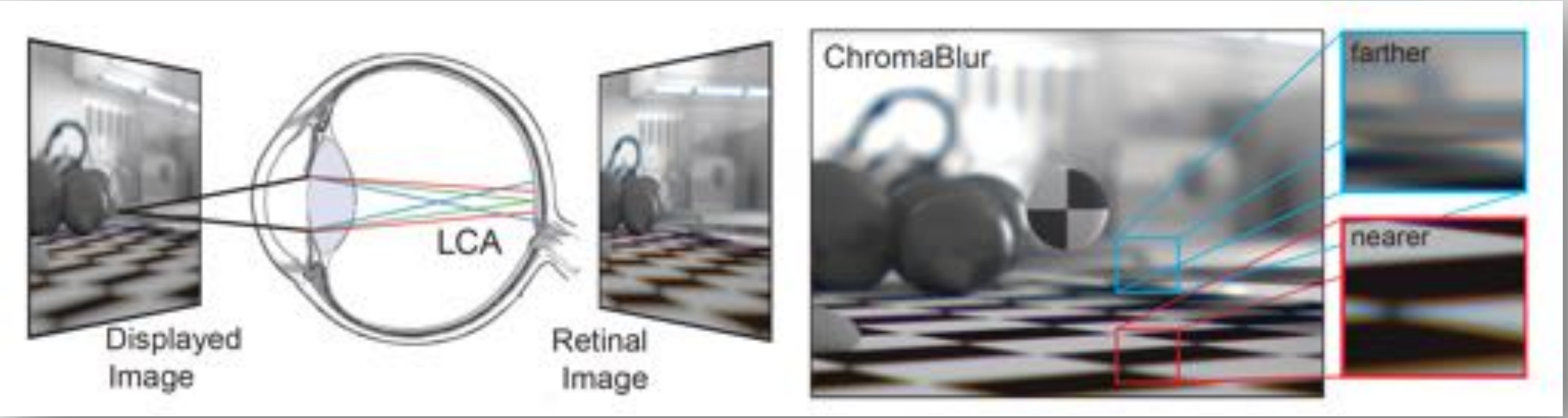
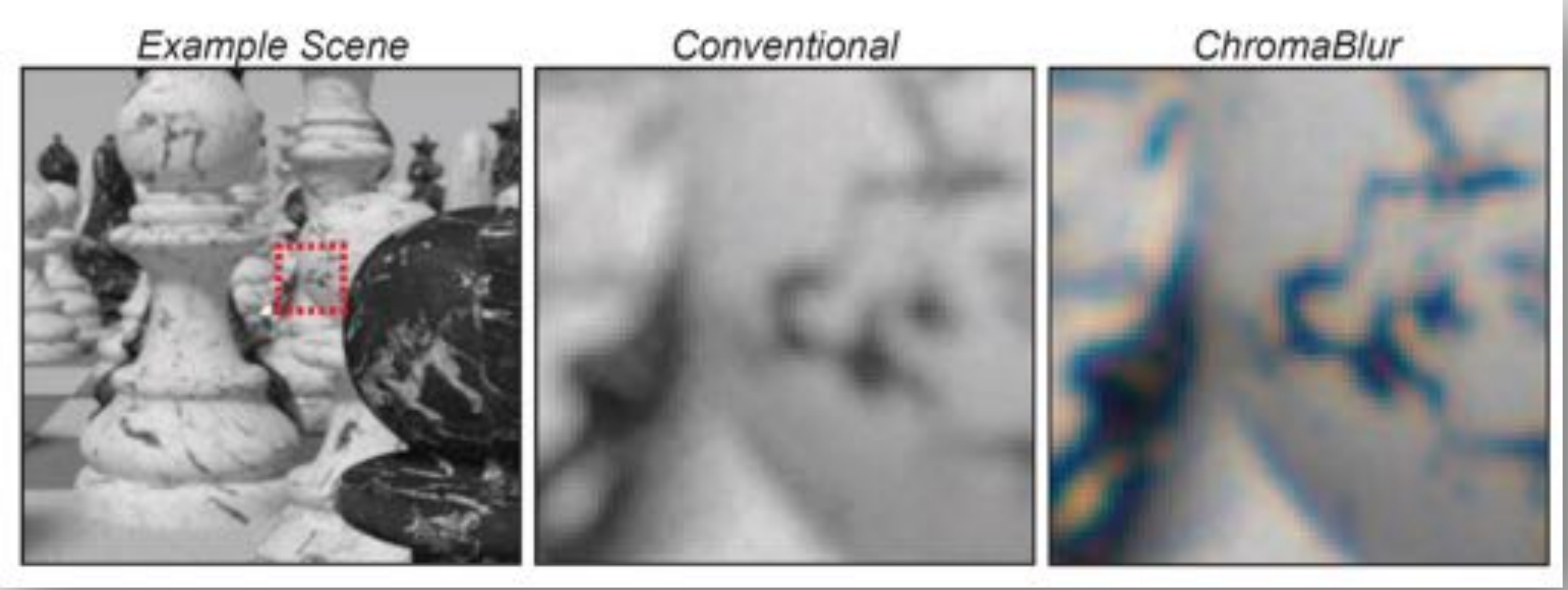
Rendering chromatic aberration



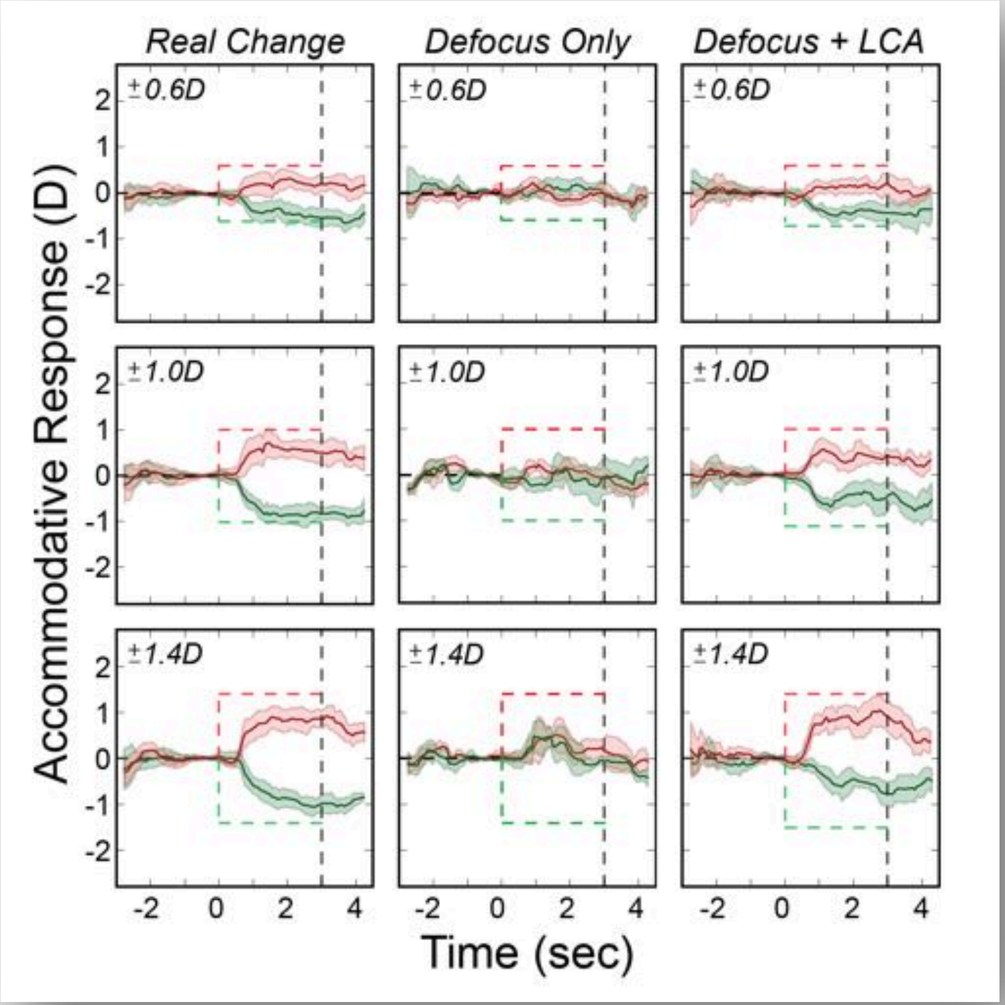
Cholewiak, S. A., Love, G. D., Srinivasan, P. P., Ng, R., & Banks, M. S. (2017). ChromaBlur: rendering chromatic eye aberration improves accommodation and realism. *ACM transactions on graphics.*, *36*(6), 210.

Rendering chromatic aberration



Cholewiak, S. A., Love, G. D., Srinivasan, P. P., Ng, R., & Banks, M. S. (2017). ChromaBlur: rendering chromatic eye aberration improves accommodation and realism. *ACM transactions on graphics.*, *36*(6), 210.

Rendering chromatic aberration



Cholewiak, S. A., Love, G. D., Srinivasan, P. P., Ng, R., & Banks, M. S. (2017). ChromaBlur: rendering chromatic eye aberration improves accommodation and realism. *ACM transactions on graphics.*, *36*(6), 210.

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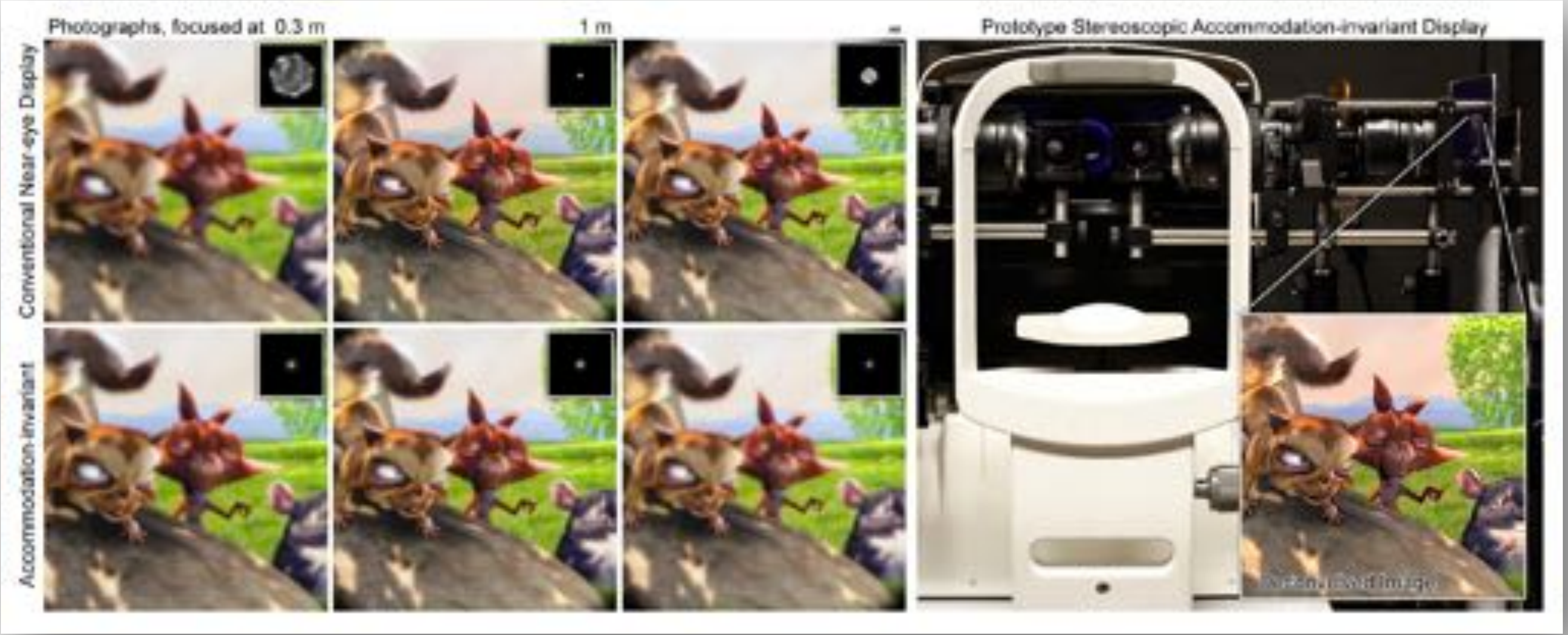
Accommodation invariant displays



Konrad, R., Padmanaban, N., Molner, K., Cooper, E. A., & Wetzstein, G. (2017). Accommodation-invariant computational near-eye displays. *ACM Transactions on Graphics (TOG)*, *36*(4), 88.

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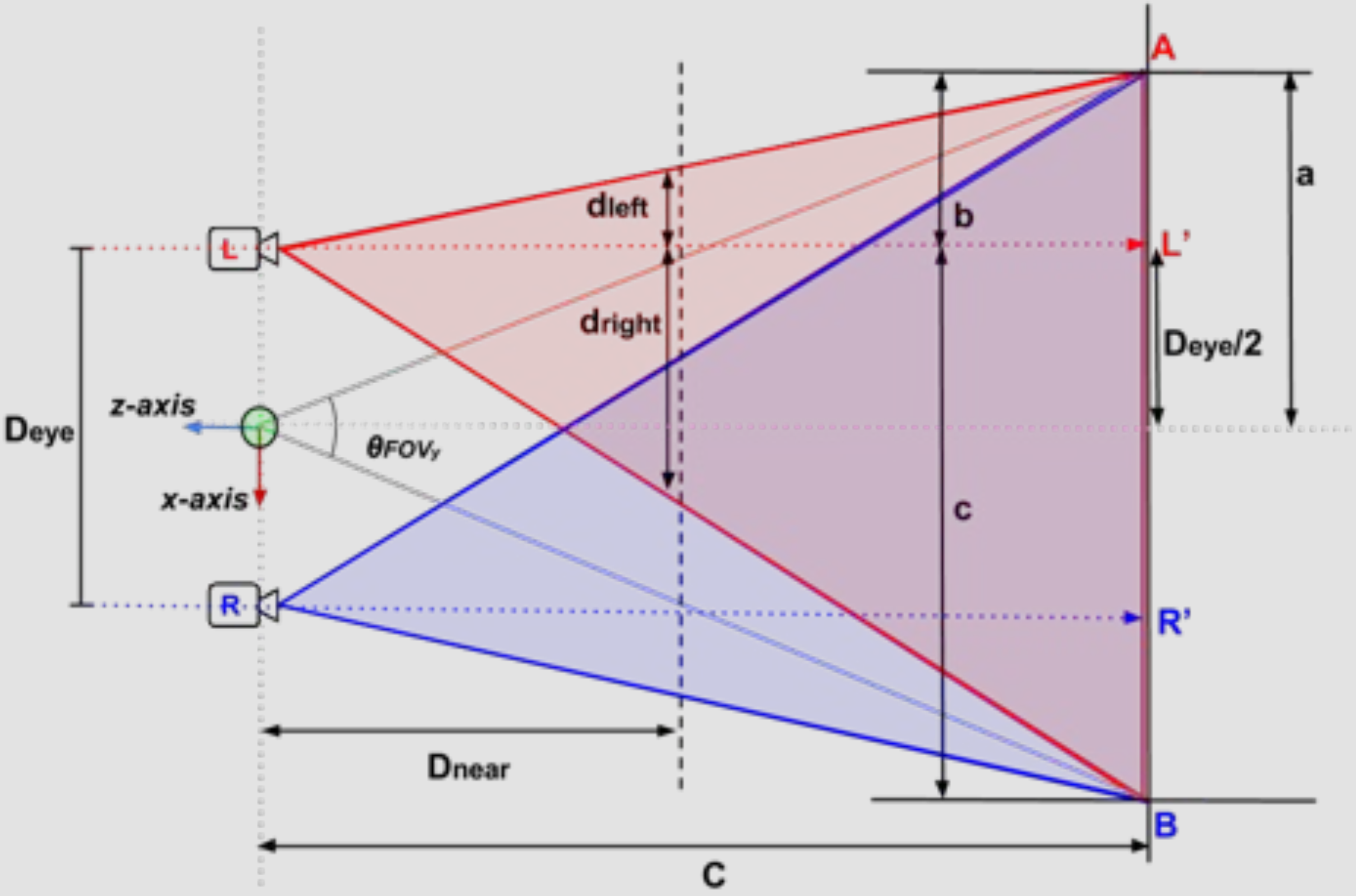
Software-only methods



Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2016, March). Gaze prediction using machine learning for dynamic stereo manipulation in games. In *Virtual Reality (VR), 2016 IEEE* (pp. 113-120). IEEE.

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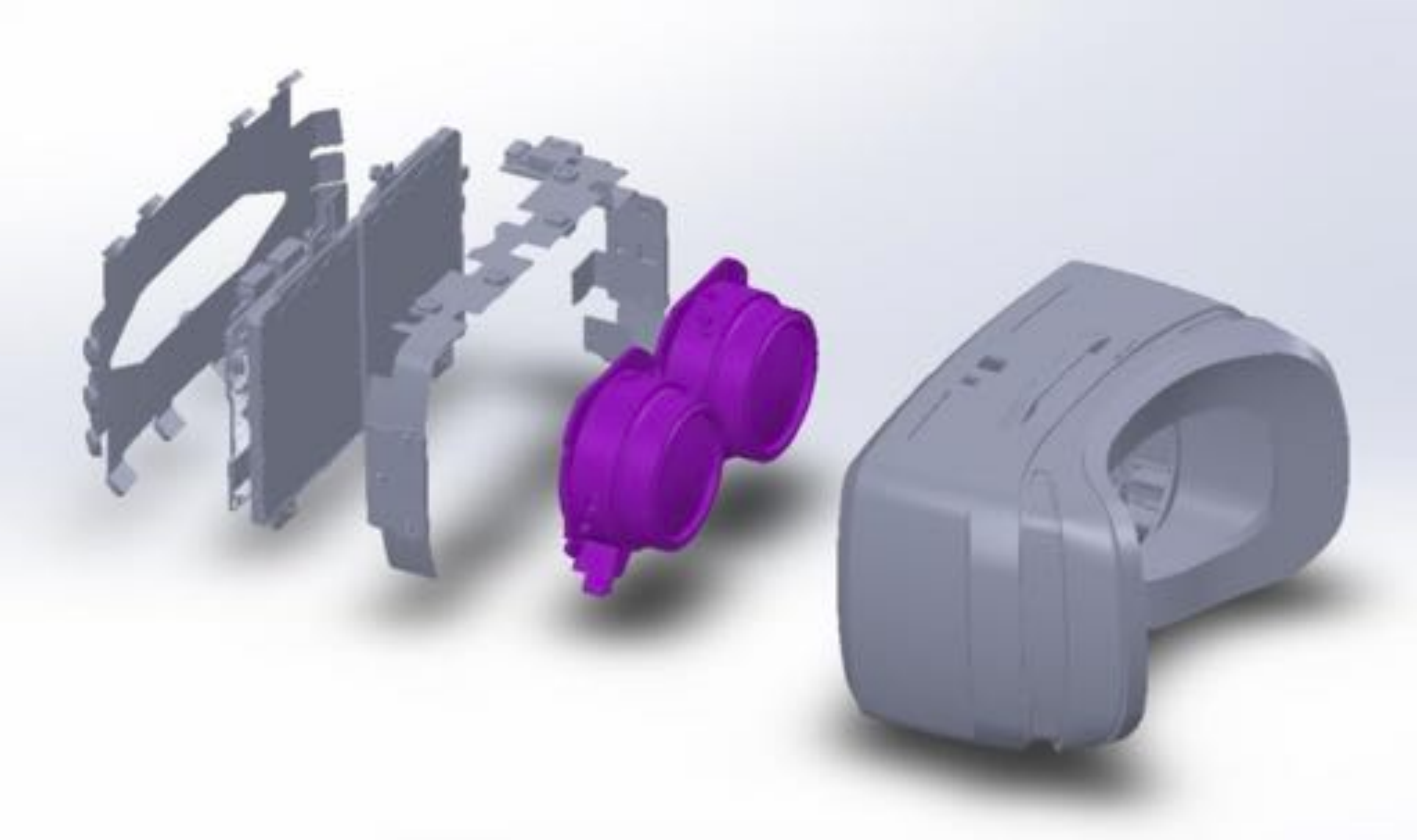
Lemnis Technologies



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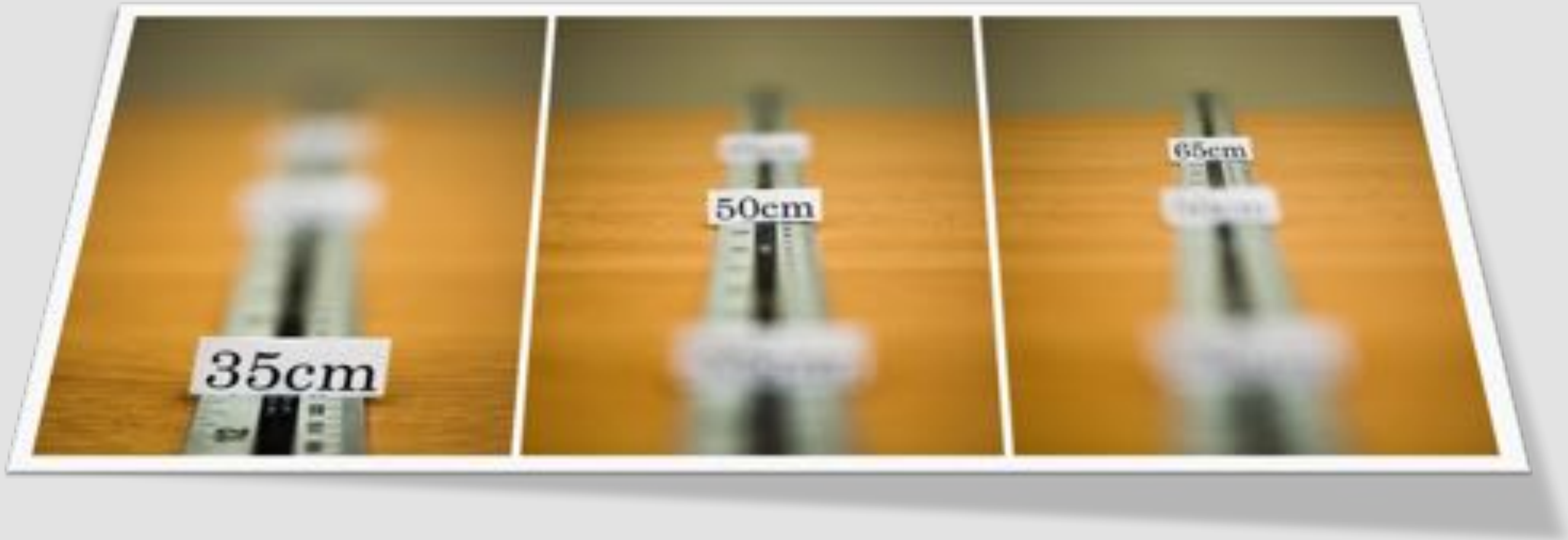
Part 3 (case study): delving deeper into the relationship of accommodation and comfort

Key, challenging ideas

- Evaluating previously proposed methods by validating if they actually drive accommodation and reduce discomfort
- Never been done before as measuring accommodation while looking through adjustable lenses is a hard problem

Investigating accommodation and comfort in head-mounted displays

1. Gaze-Contingent Depth-of-Field blur (GC DoF blur)
   Mauderer et al. (2014)



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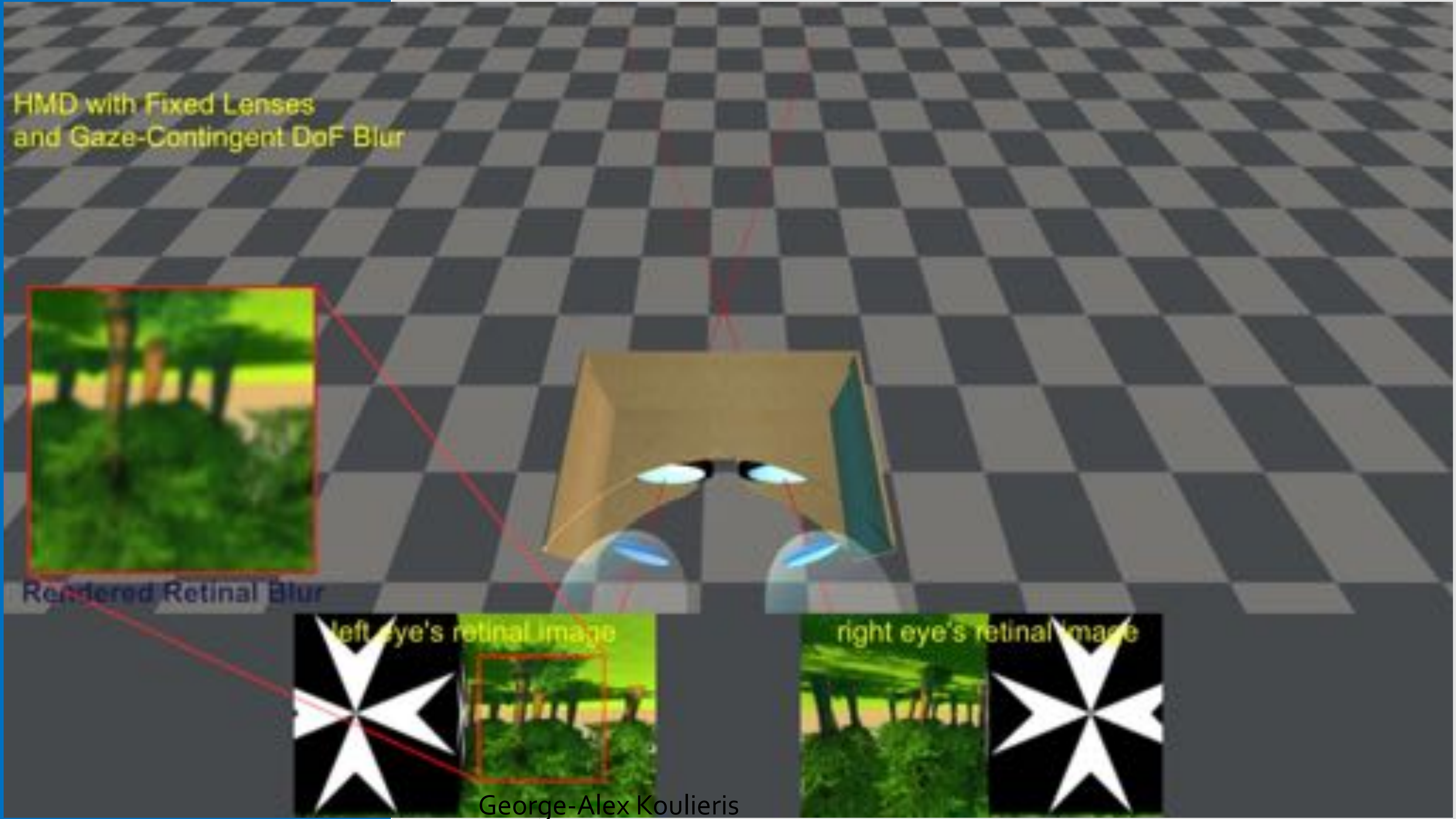
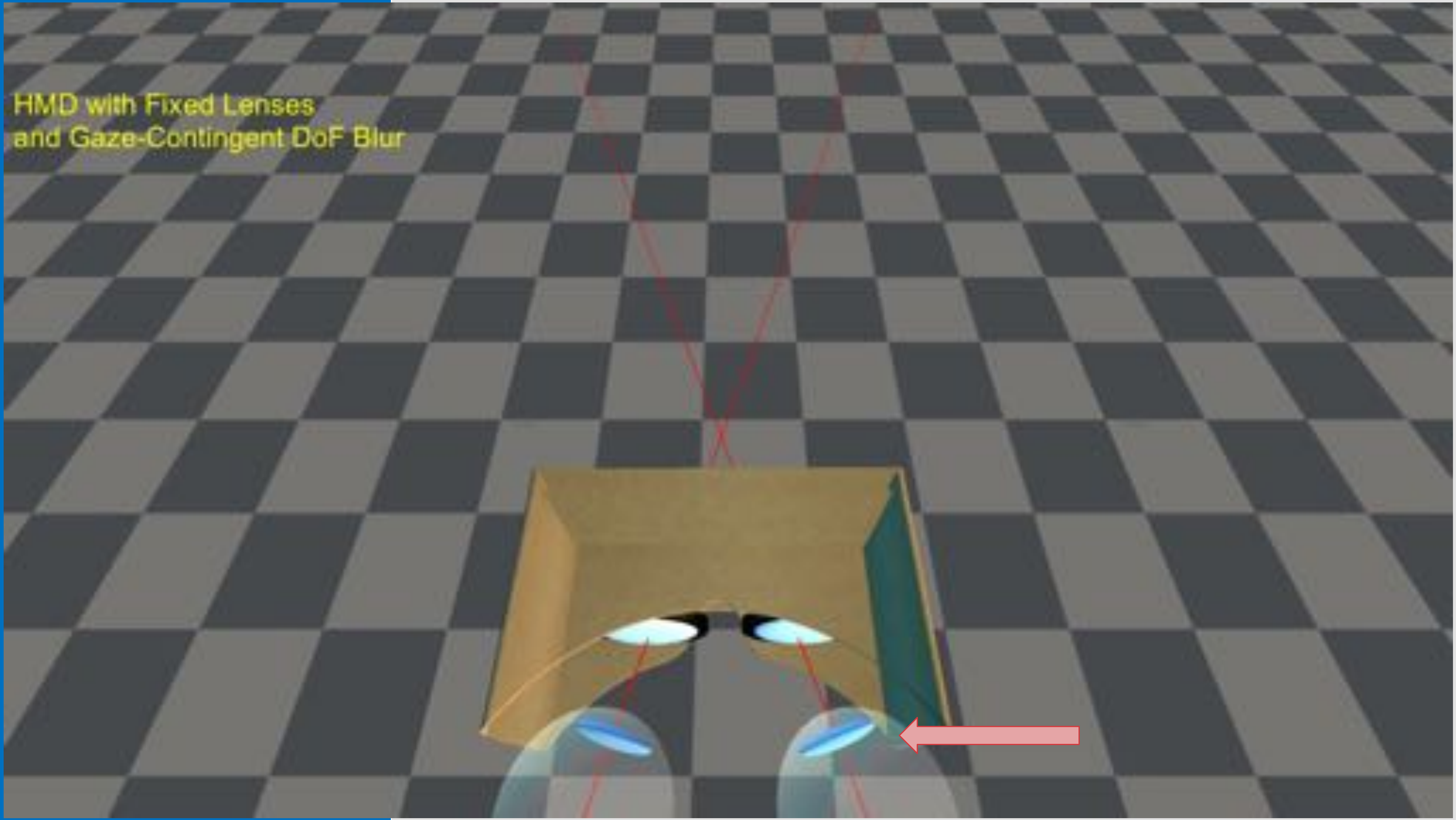

HMD with Fixed Lenses
and Gaze-Contingent DoF Blur
Rendered Retinal Blur
left eye's retinal image
right eye's retinal image


HMD with Fixed Lenses
and Gaze-Contingent DoF Blur

Investigating accommodation and comfort in head-mounted displays

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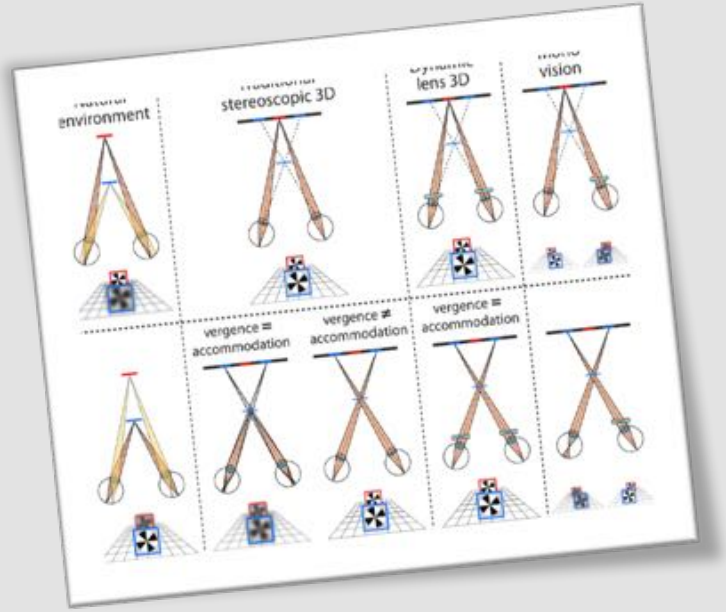
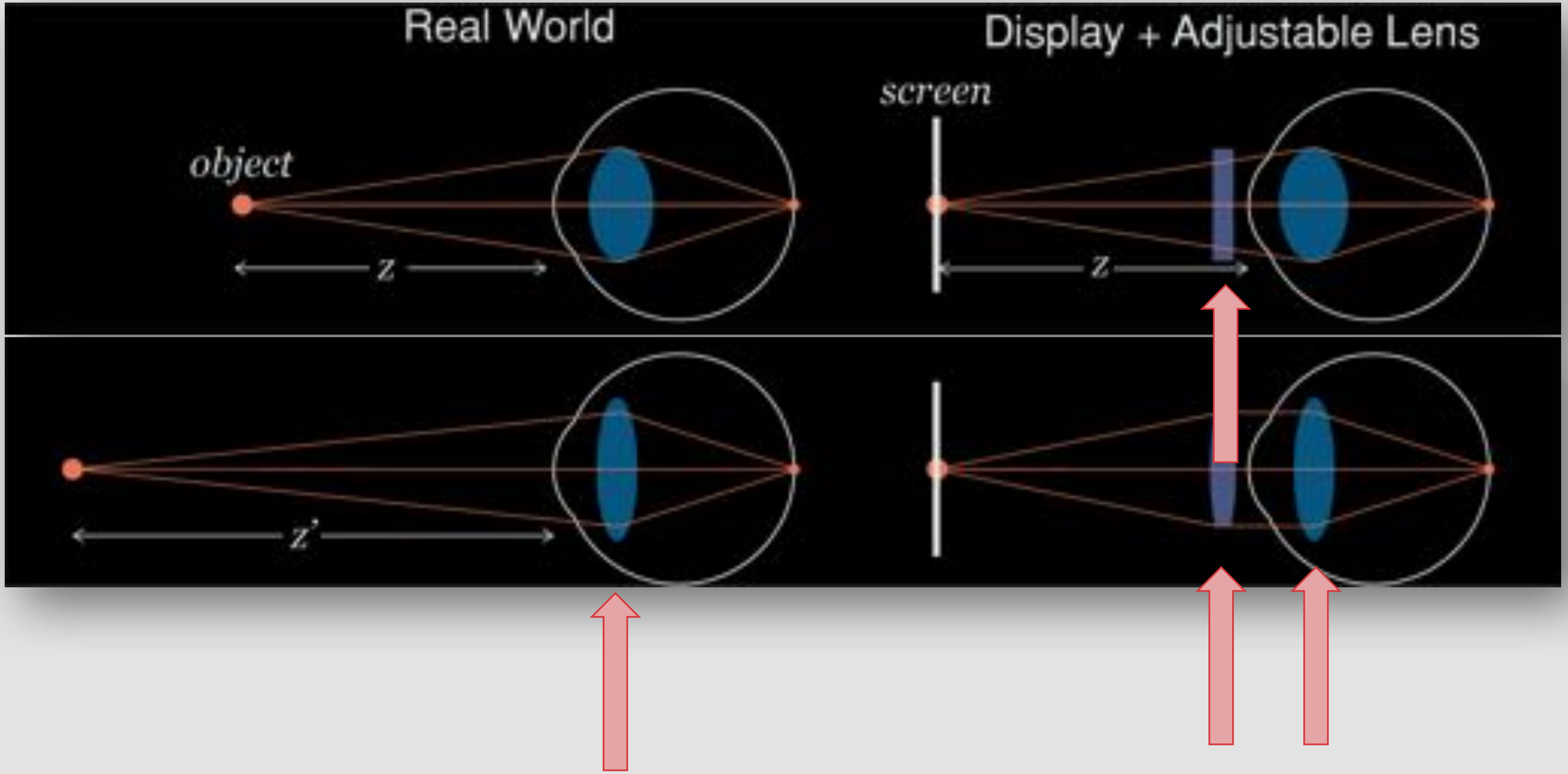
1. Gaze-Contingent Depth-of-Field blur (GC DoF blur)
   Mauderer et al. (2014)
2. Focus-Adjustable lenses & GC DoF Blur
   Johnson et al. (2016); Konrad et al. (2016)



Focus-adjustable lenses



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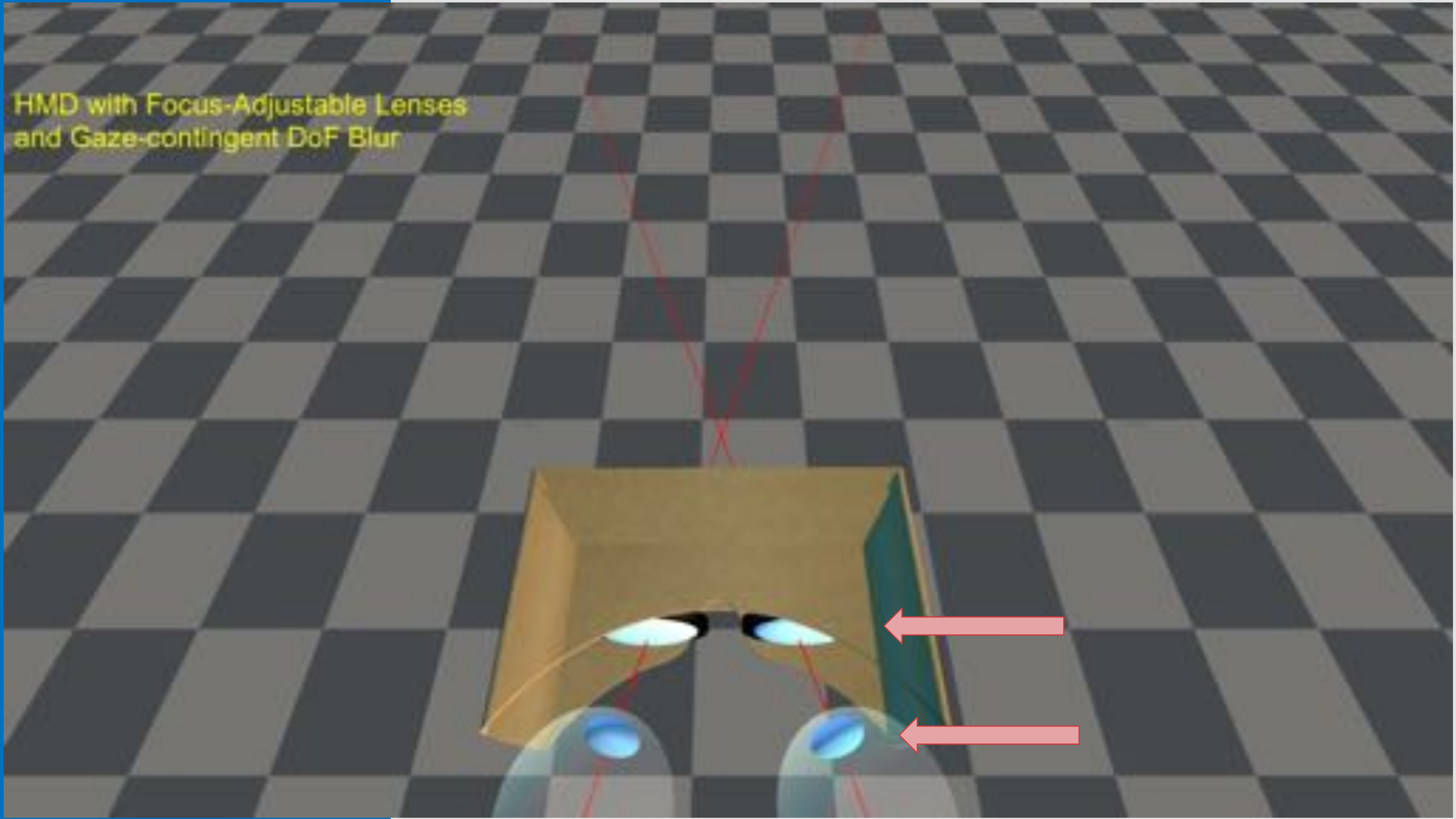
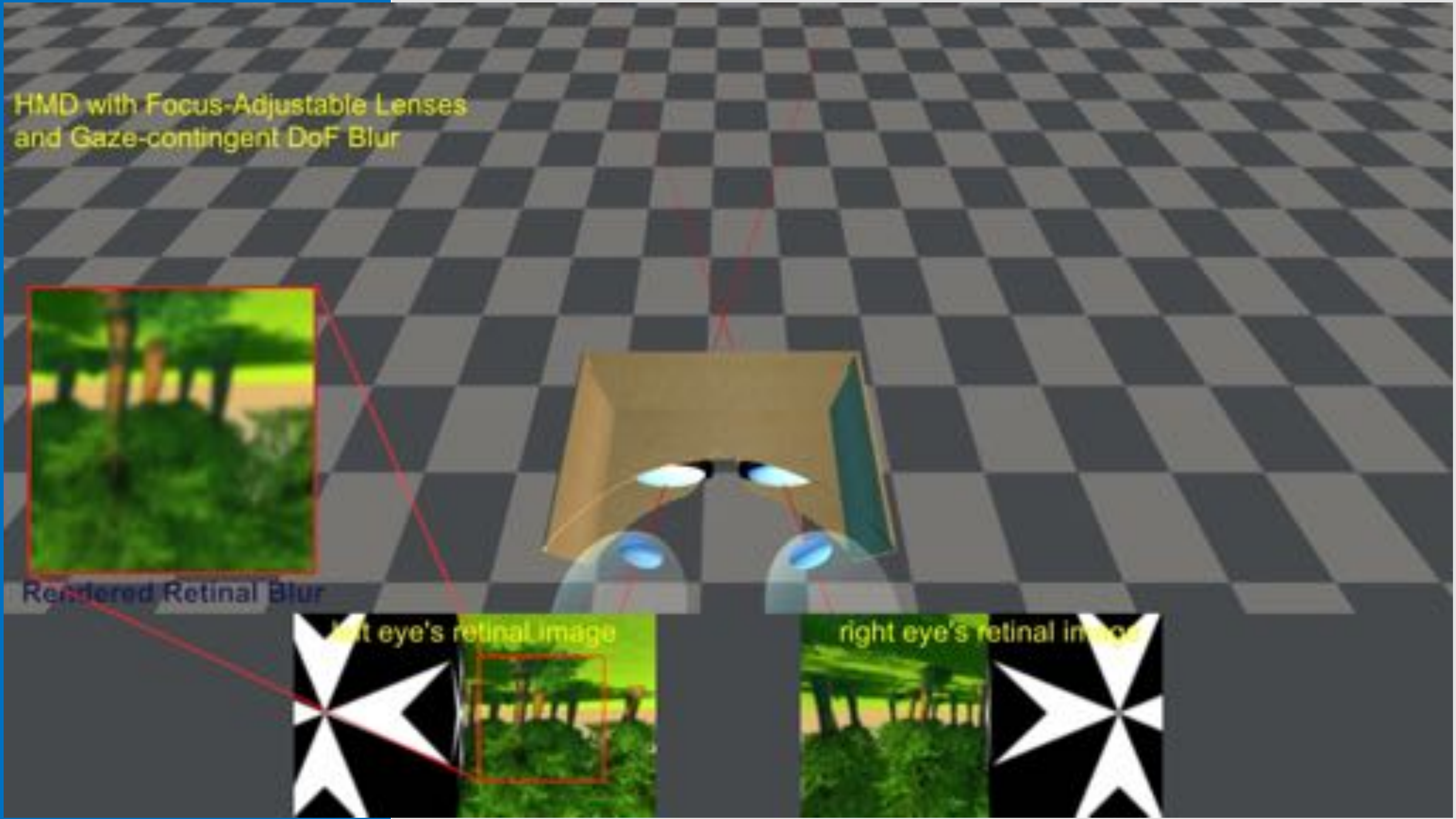
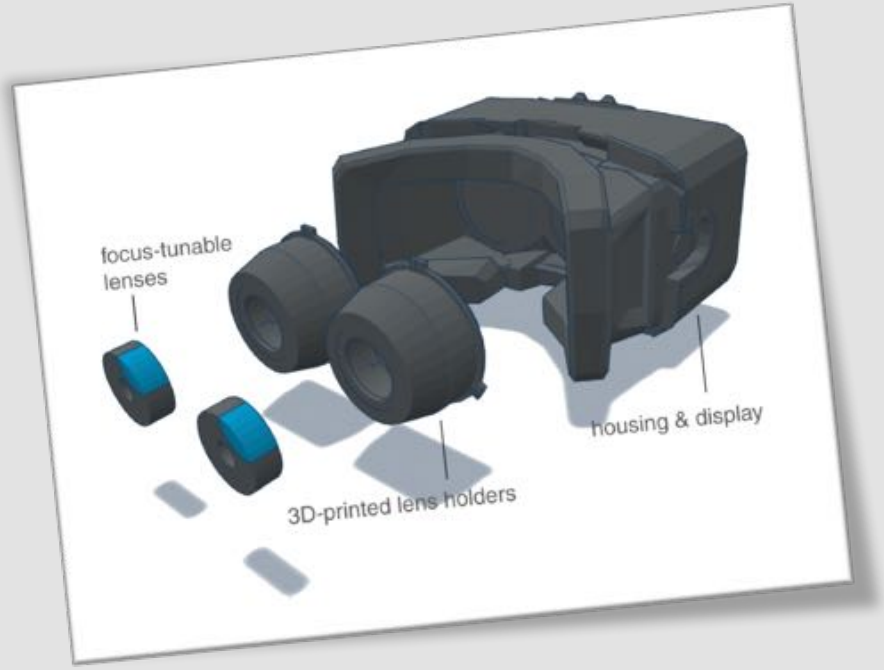

HMD with Focus-Adjustable Lenses
and Gaze-contingent DoF Blur


HMD with Focus-Adjustable Lenses
and Gaze-contingent DoF Blur
Rendered Retinal Blur

Investigating accommodation and comfort in head-mounted displays

1. Gaze-Contingent Depth-of-Field blur (GC DoF blur)
   Mauderer et al. (2014)
2. Focus-Adjustable lenses & GC DoF Blur
   Johnson et al. (2016); Konrad et al. (2016)
3. Monovision
   Johnson et al. (2016); Konrad et al. (2016)



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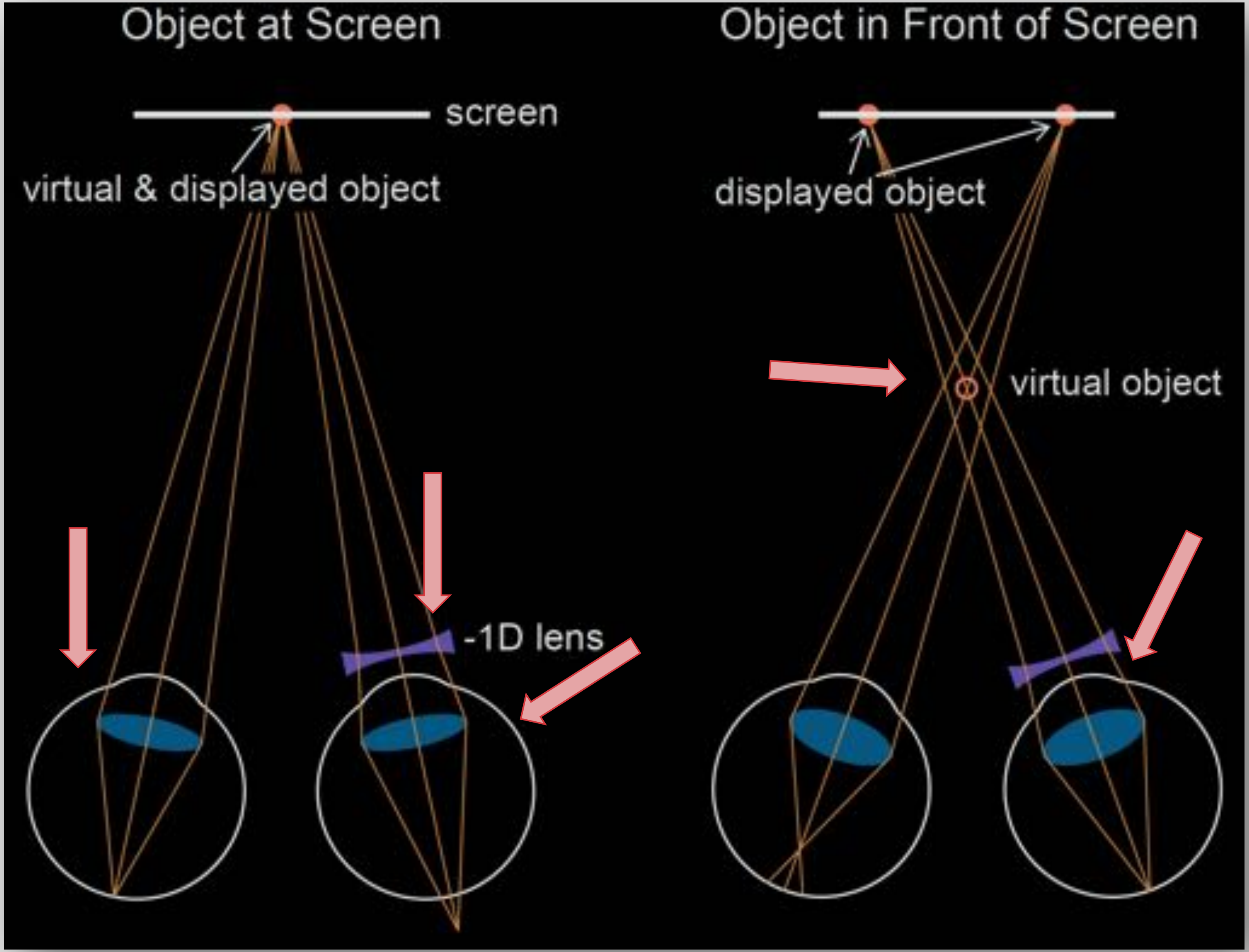
Monovision



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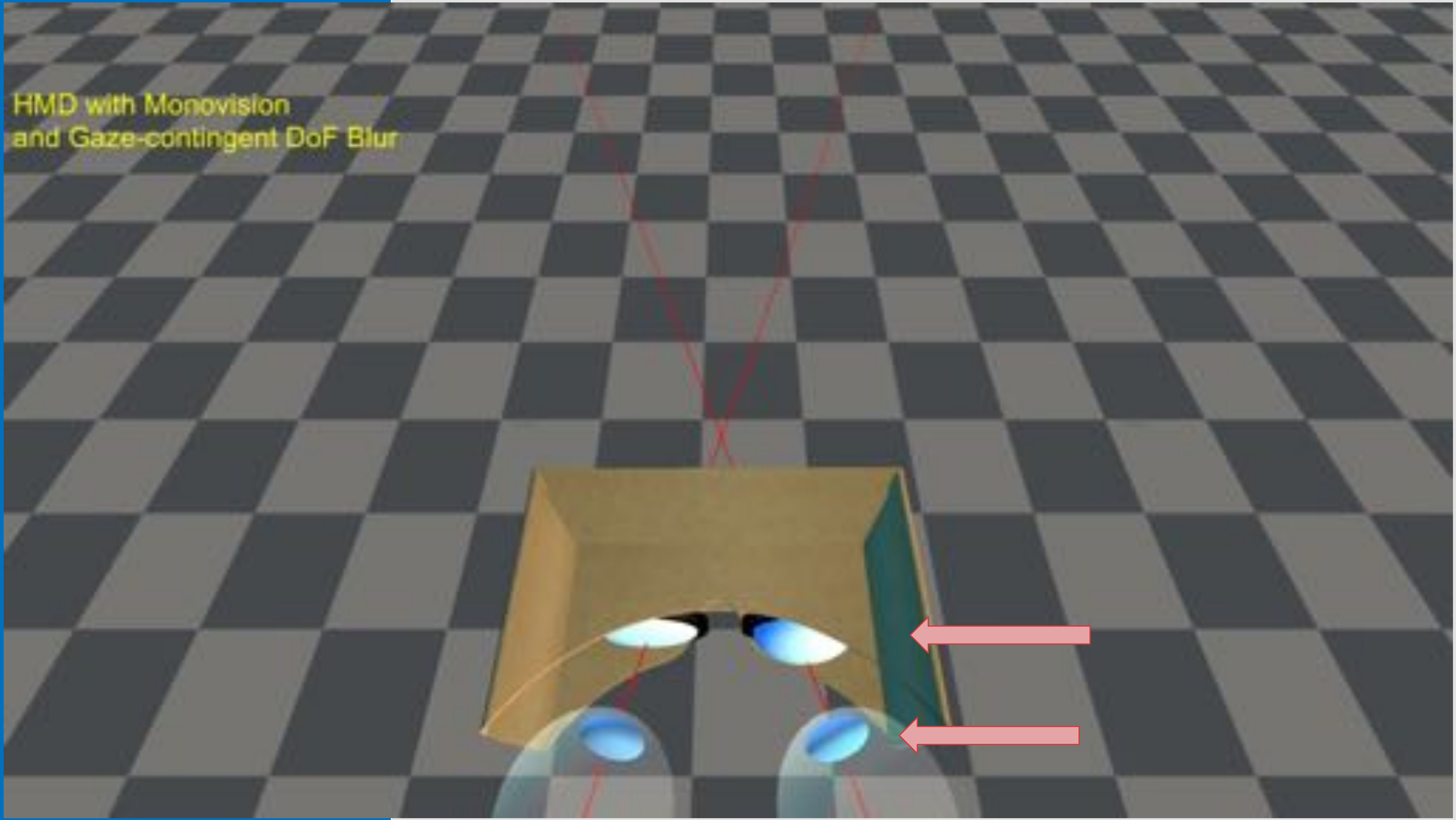
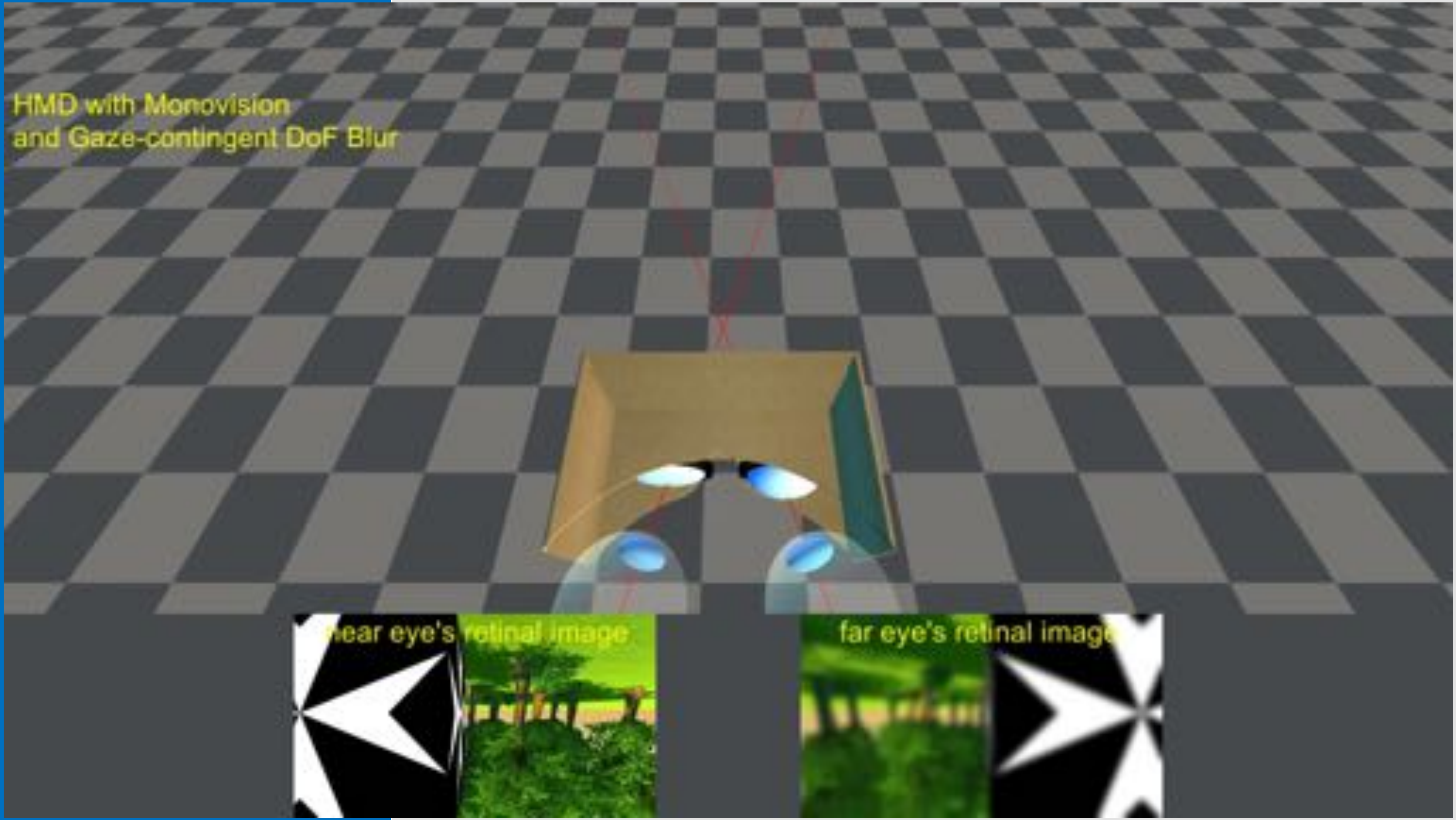

HMD with Monovision
and Gaze-contingent DoF Blur


HMD with Monovision
and Gaze-contingent DoF Blur
near eye's retinal image
far eye's retinal image

Hypotheses

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Gaze-Contingent Depth-of-Field blur (GC DoF blur)
- Correct retinal blur
- Should not drive accommodation

Focus-Adjustable lenses & GC DoF blur
- Correct retinal blur
- Hypothesized to drive accommodation

Monovision
- Correct blur on one retina at a time
- Only two accommodation planes: near/far

Evaluation of proposed configurations

1. Accommodation driven correctly?
2. Improved comfort?

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The measurement device

The measurement device

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The measurement device

The measurement device

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Experimental details

Fixed vs Focus-Adjustable lens conditions

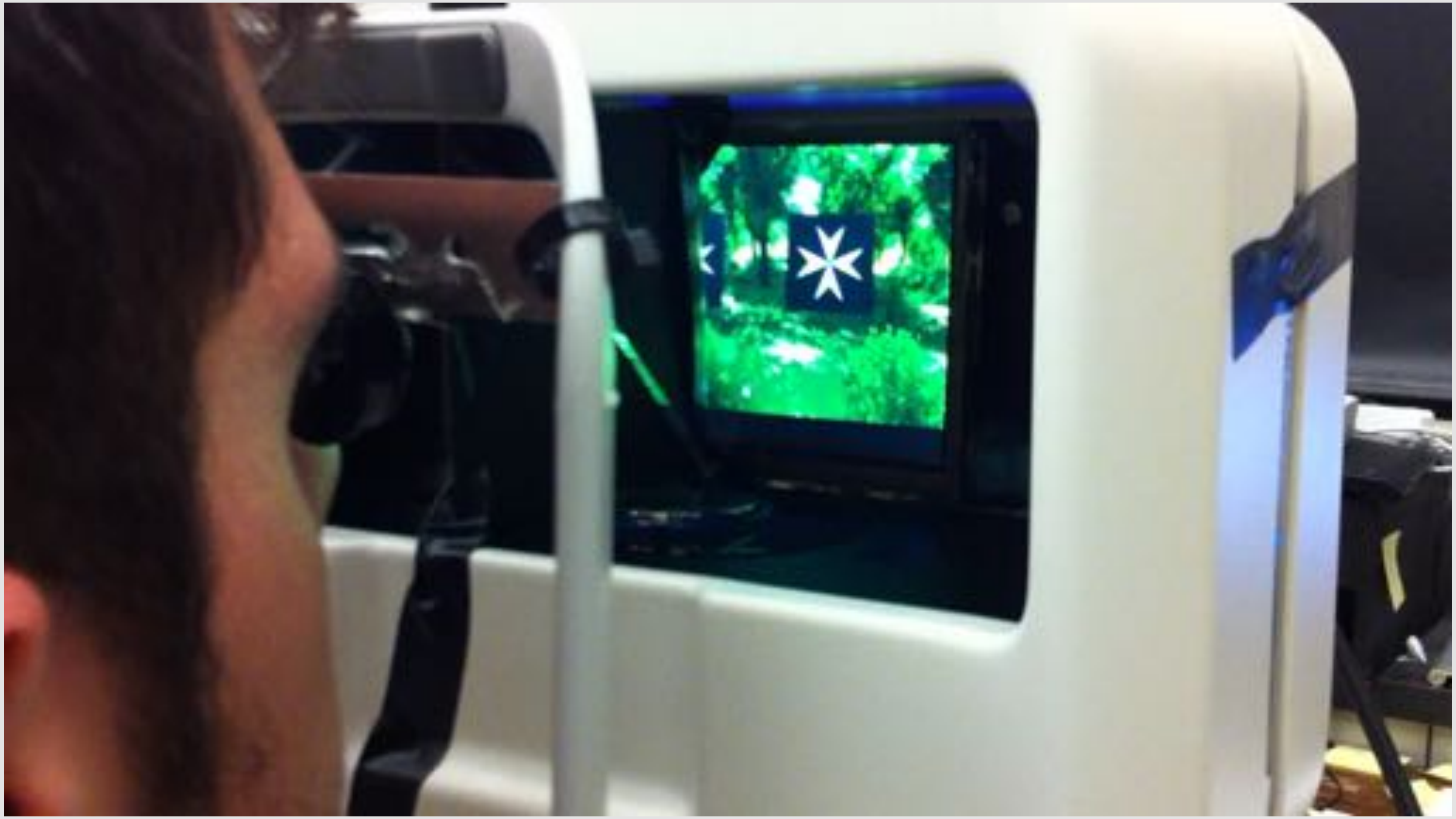
16 conditions, factorial combination of :

- depth-of-field
- focus-adjustable lenses
- target speed
- binocular/monocular

Monovision conditions

8 conditions

Accommodation measurements



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Accommodation measurements

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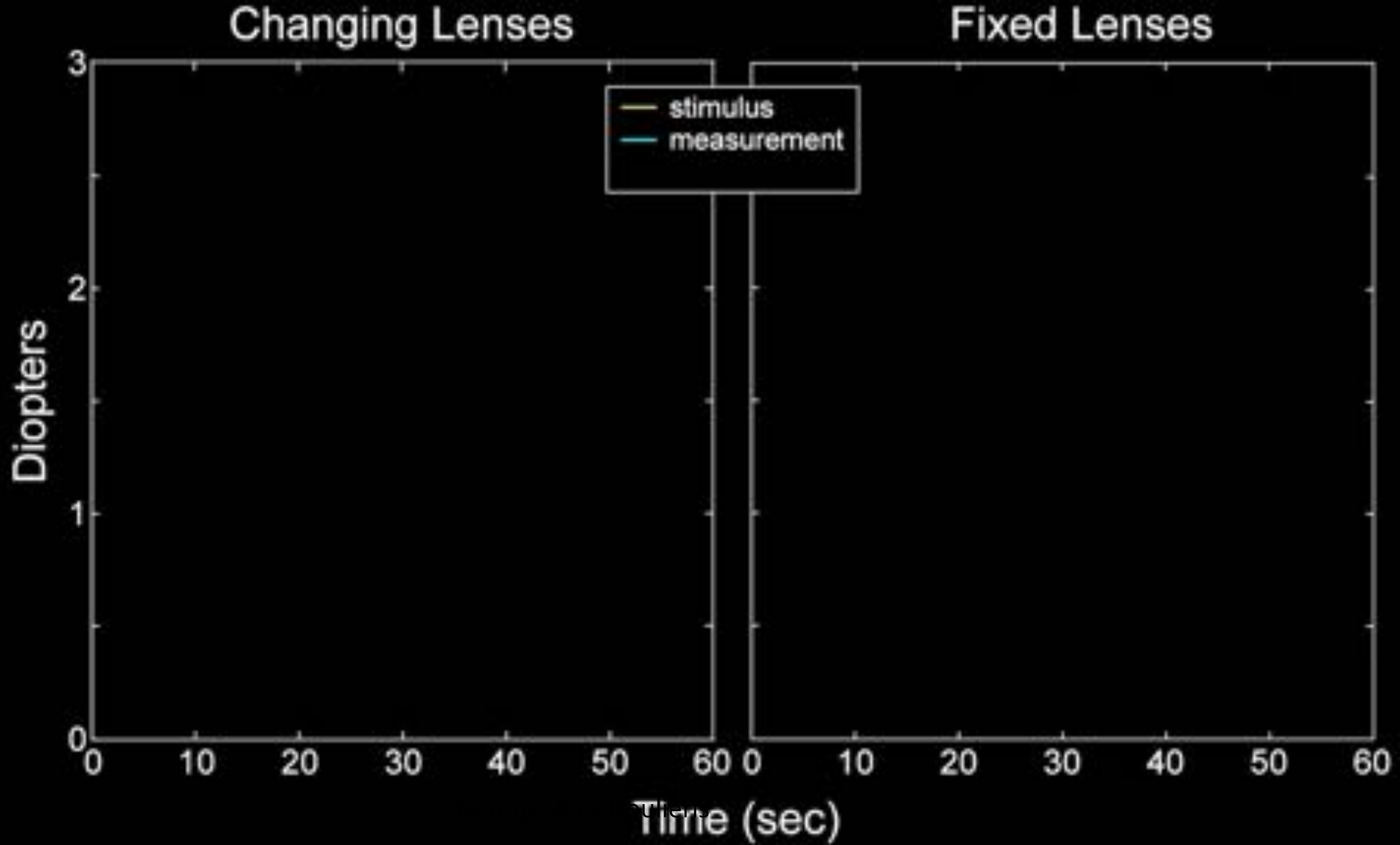
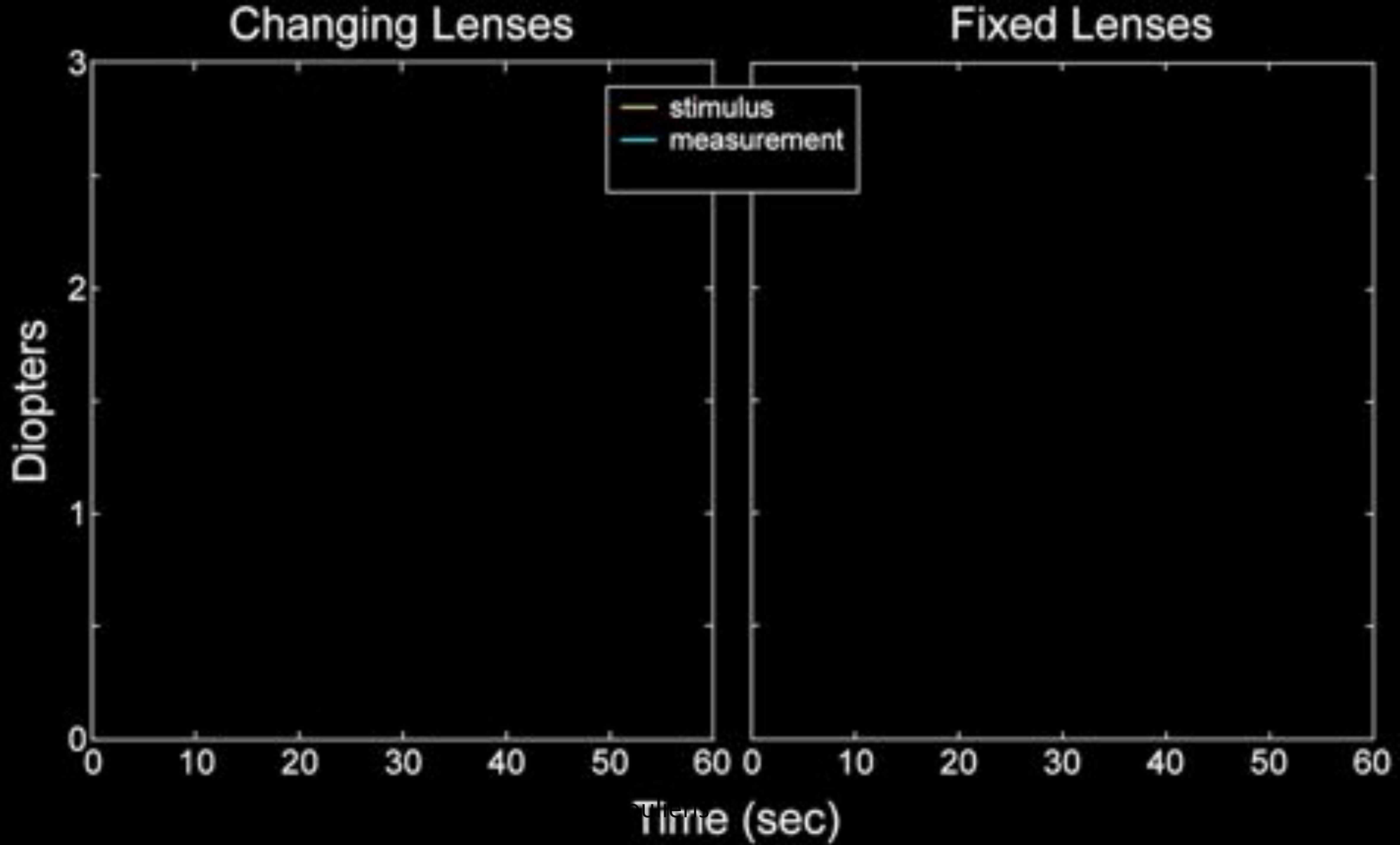

Changing Lenses
Fixed Lenses
stimulus
measurement
Diopters
0
1
2
3
0
10
20
30
40
50
60
0
10
20
30
40
50
60
Time (sec)


Changing Lenses
Fixed Lenses
stimulus
measurement
Diopters
0
1
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20
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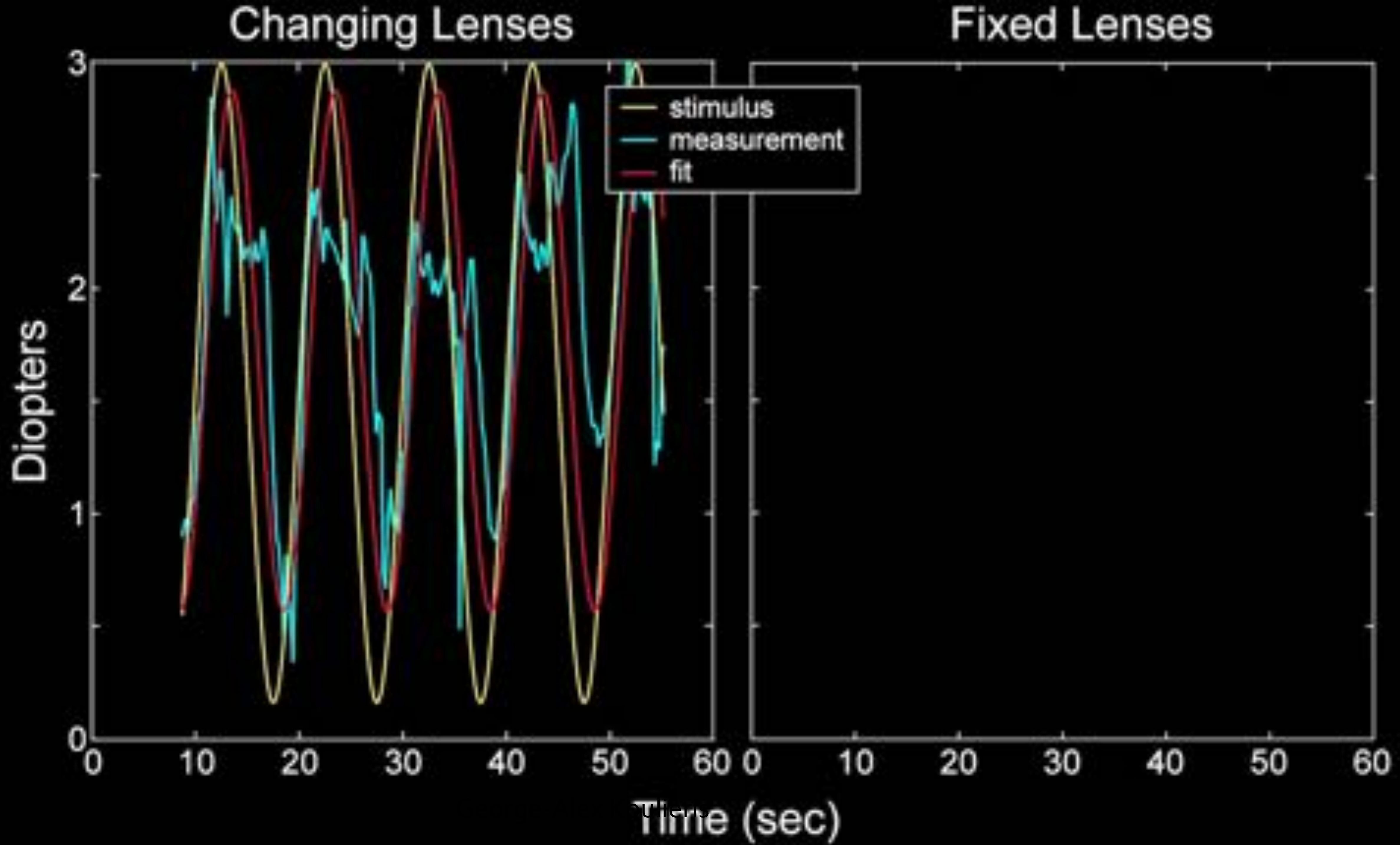
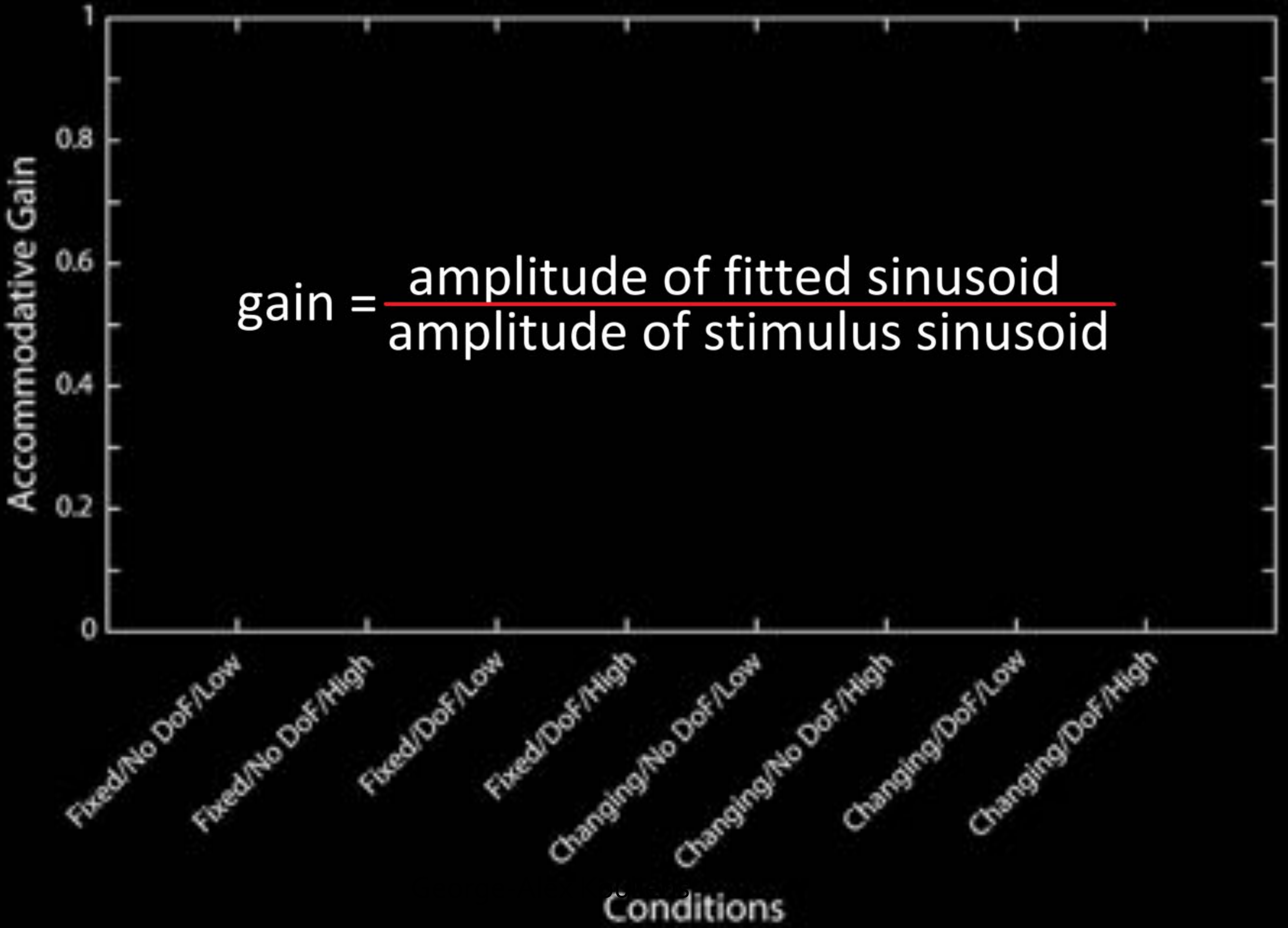
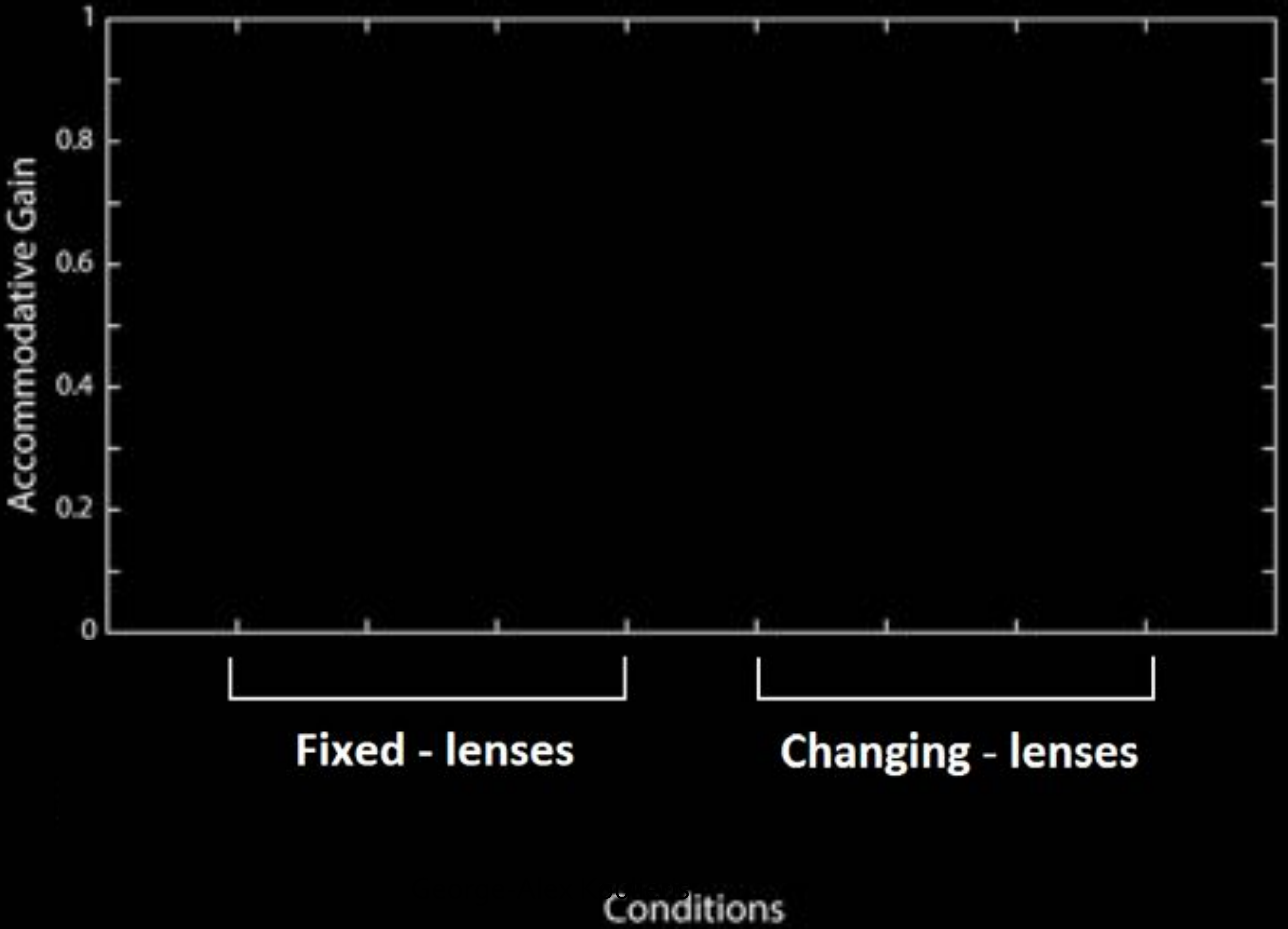
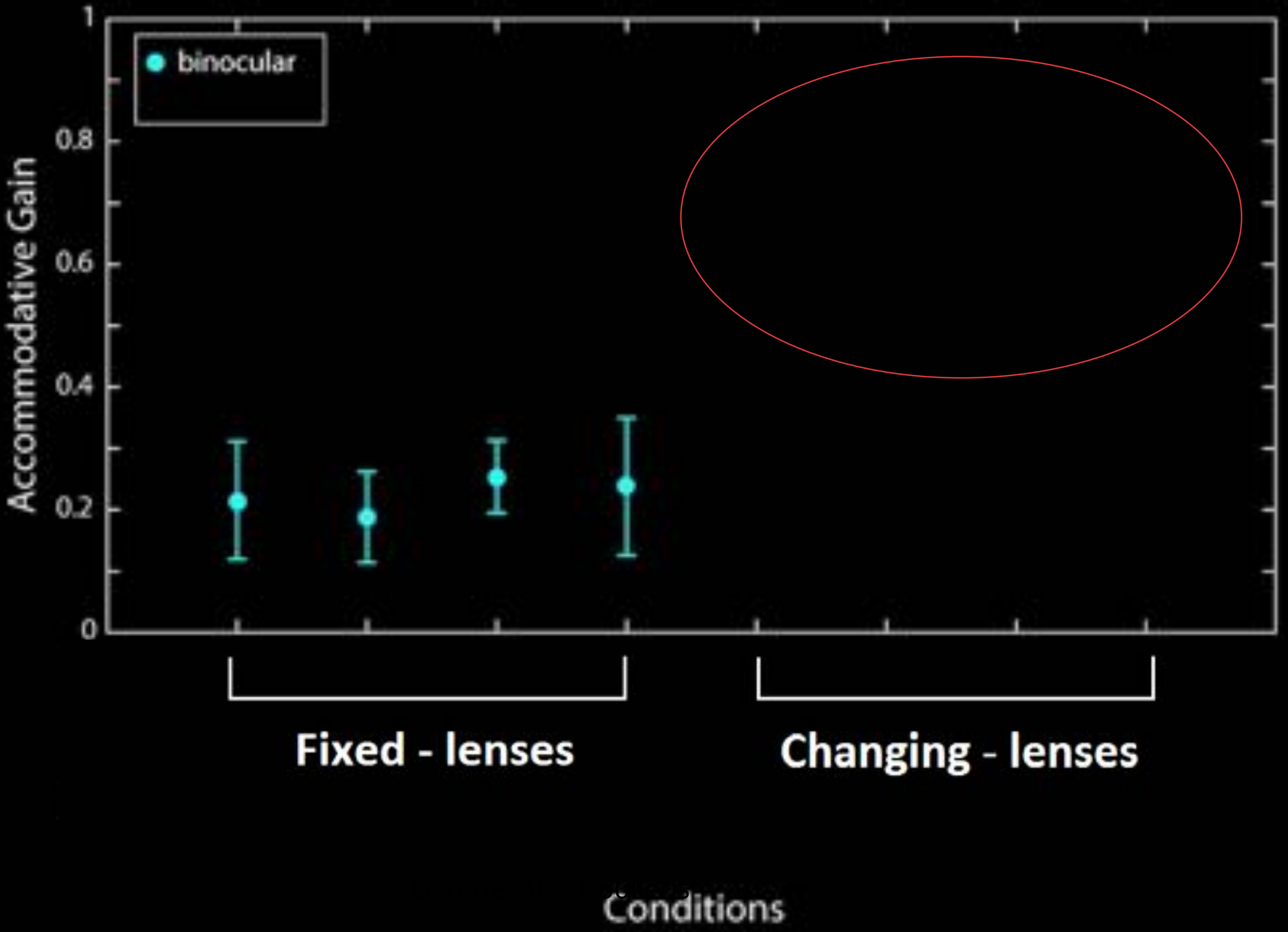
60
Time (sec)

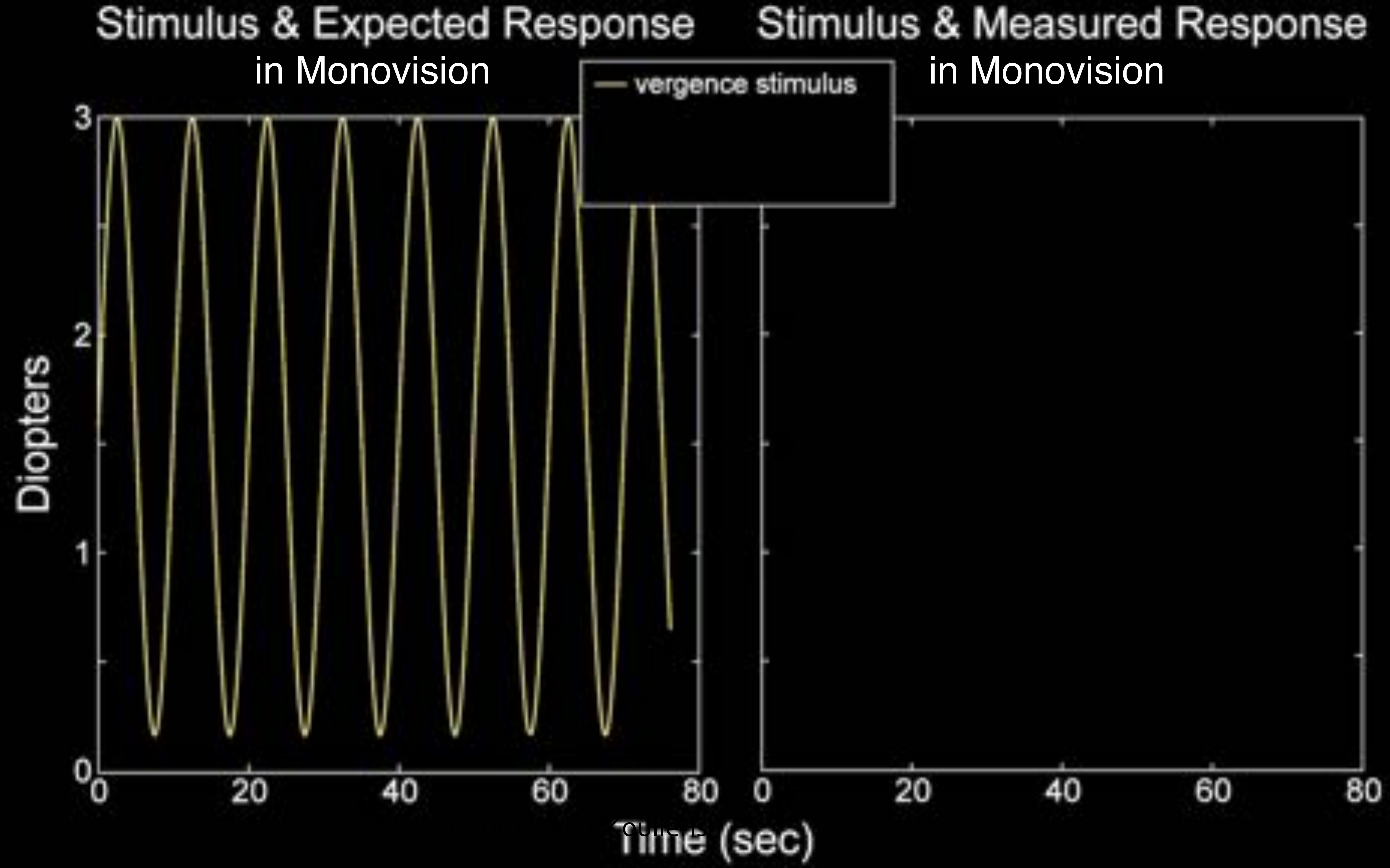

Changing Lenses
Fixed Lenses
stimulus
measurement
fit
Diopters
0
1
2
3
0
10
20
30
40
50
60
Time (sec)

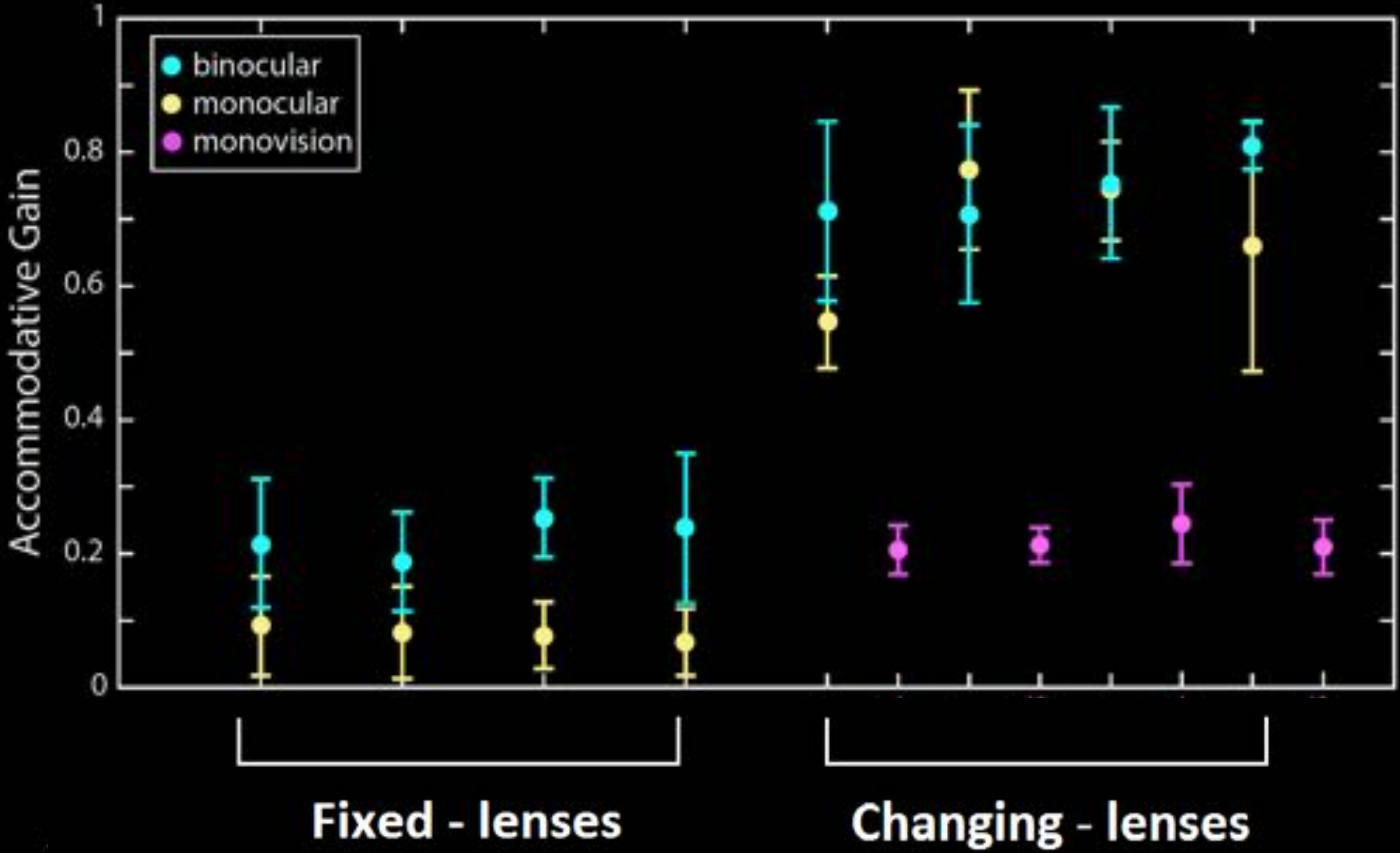


$$\text{gain} = \frac{\text{amplitude of fitted sinusoid}}{\text{amplitude of stimulus sinusoid}}$$

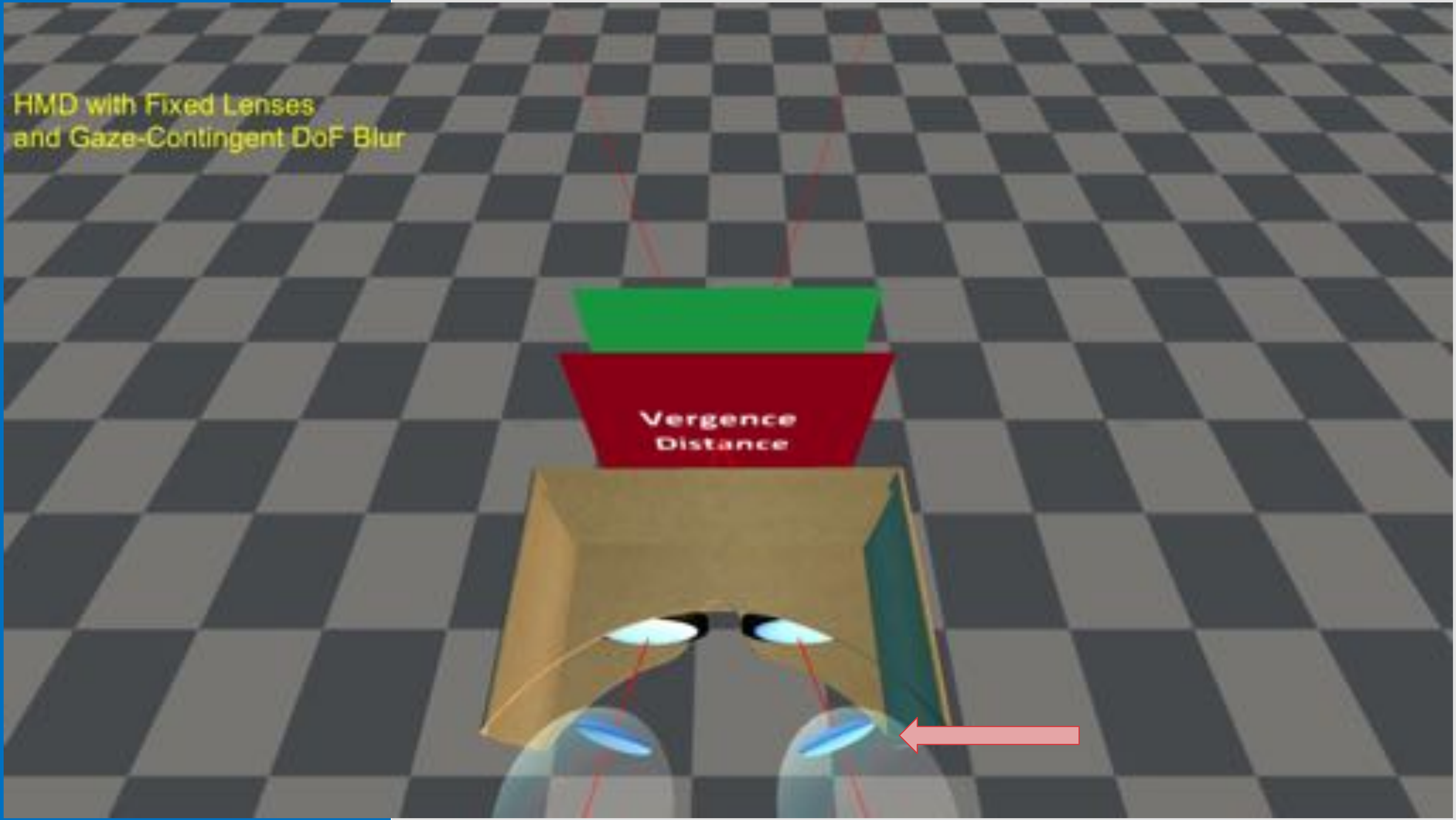

Accommodative Gain
1
0.8
0.6
0.4
0.2
0
Fixed - lenses
Changing - lenses
Conditions

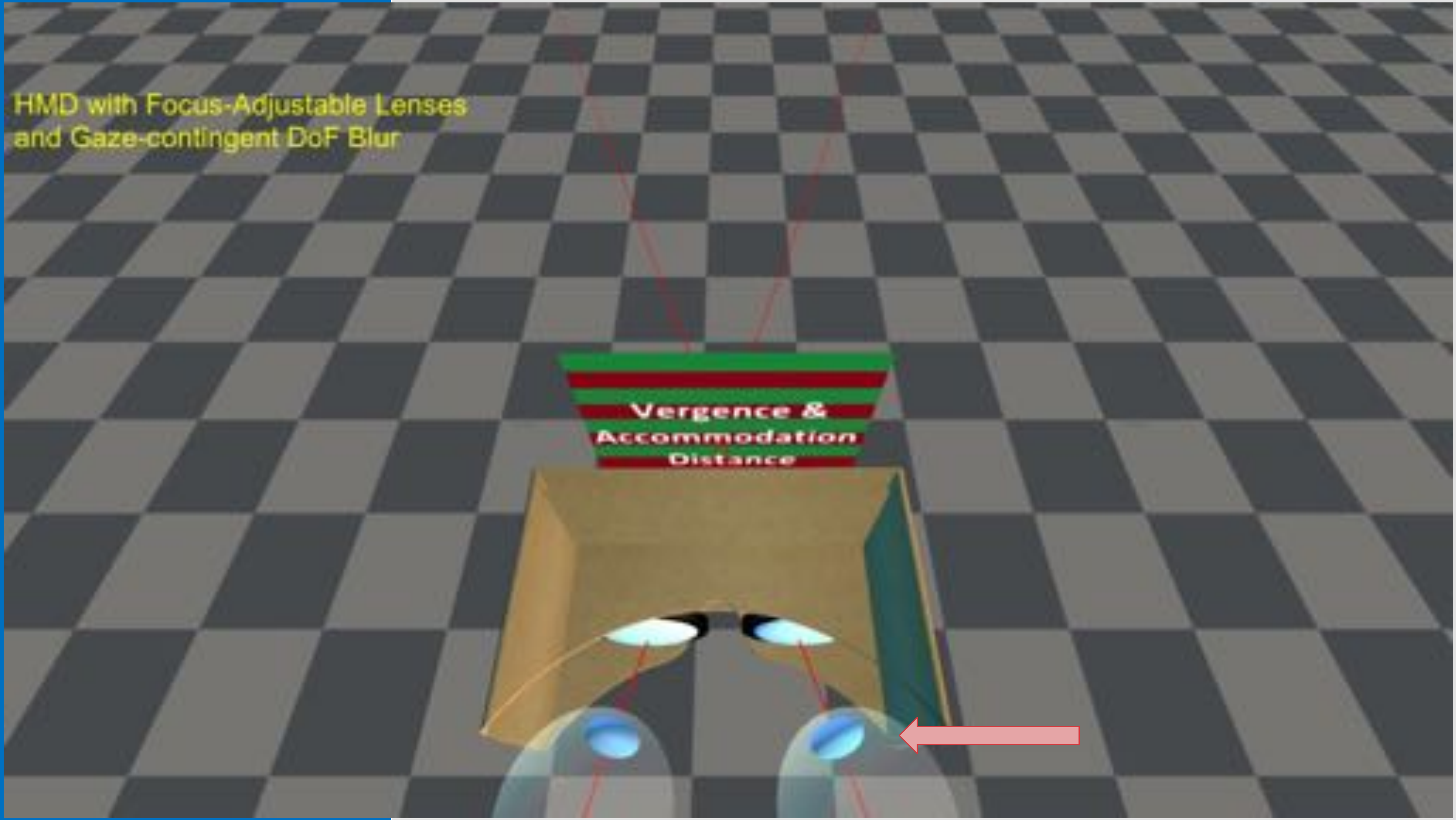

binocular
Accommodative Gain
0
0.2
0.4
0.6
0.8
1
Fixed - lenses
Changing - lenses
Conditions

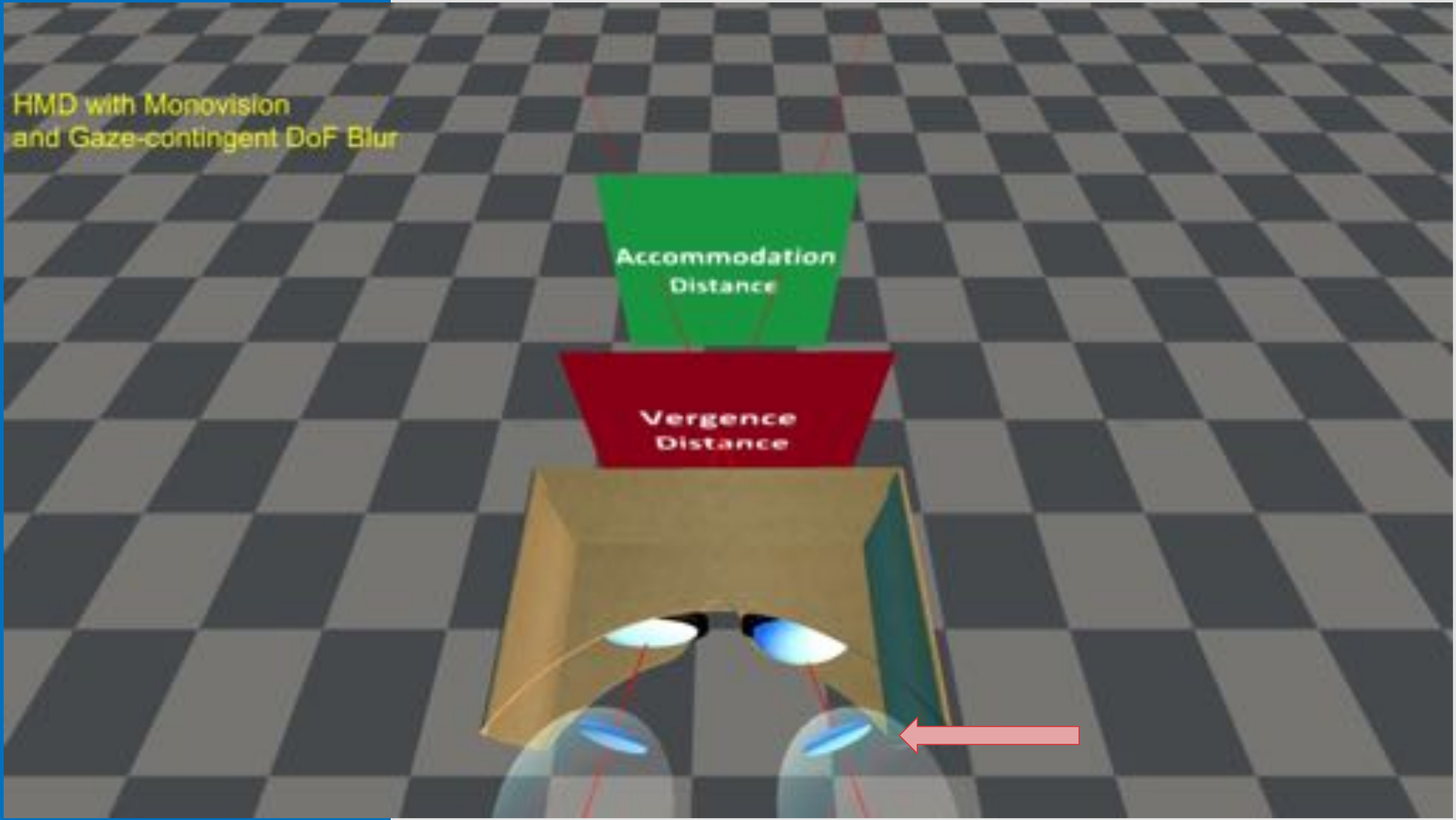

Stimulus & Expected Response
in Monovision
Stimulus & Measured Response
in Monovision
vergence stimulus
Diopters
Time (sec)
3
2
1
0
0
20
40
60
80
0
20
40
60
80


binocular
monocular
monovision
Accommodative Gain
1
0.8
0.6
0.4
0.2
0
Fixed - lenses
Changing - lenses

Conditions


HMD with Fixed Lenses
and Gaze-Contingent DoF Blur
Vergence
Distance


HMD with Focus-Adjustable Lenses
and Gaze-contingent DoF Blur
Vergence &
Accommodation
Distance


HMD with Monovision
and Gaze-contingent DoF Blur
Accommodation
Distance
Vergence
Distance

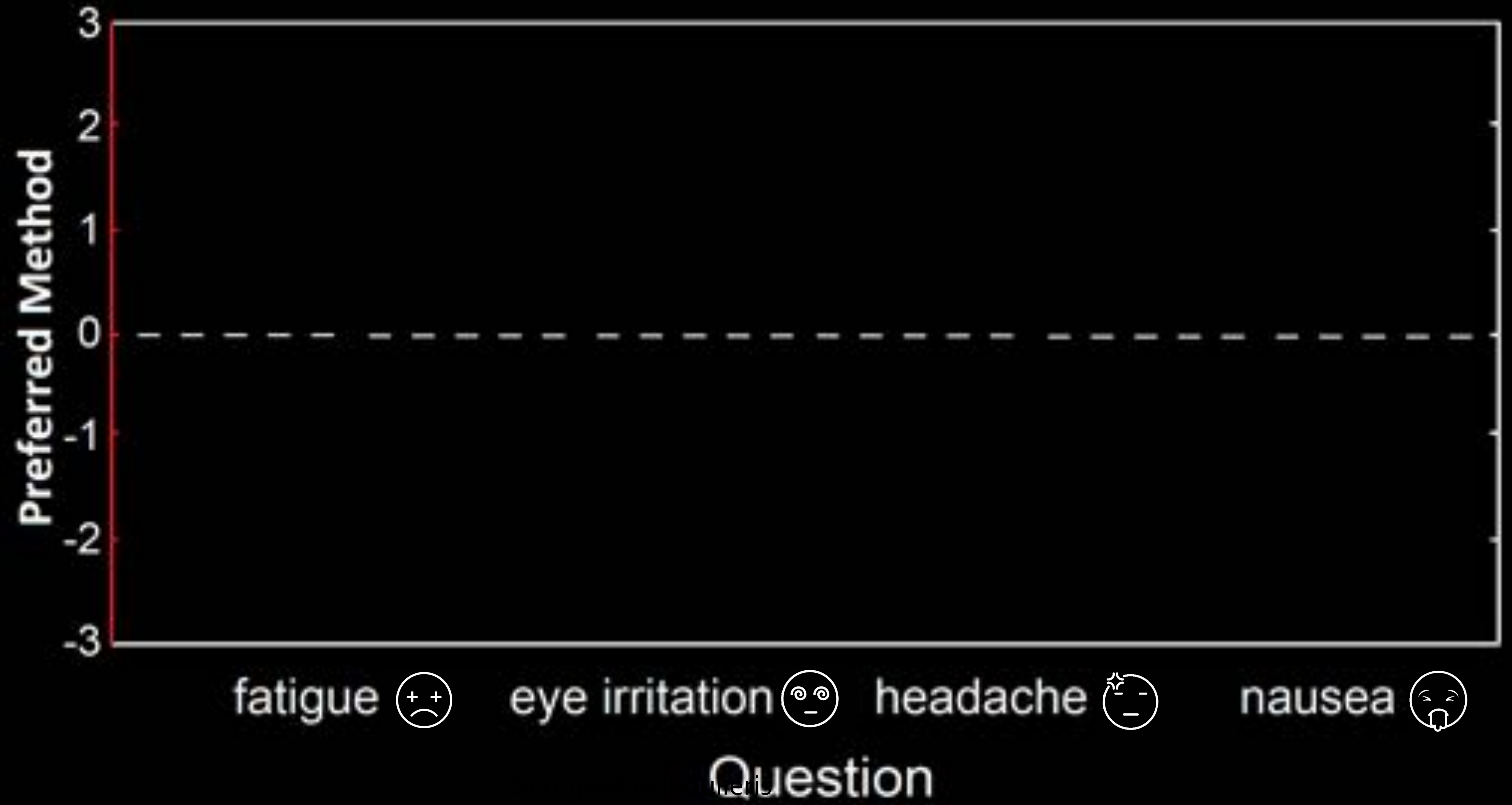
Predictions from the accommodation data

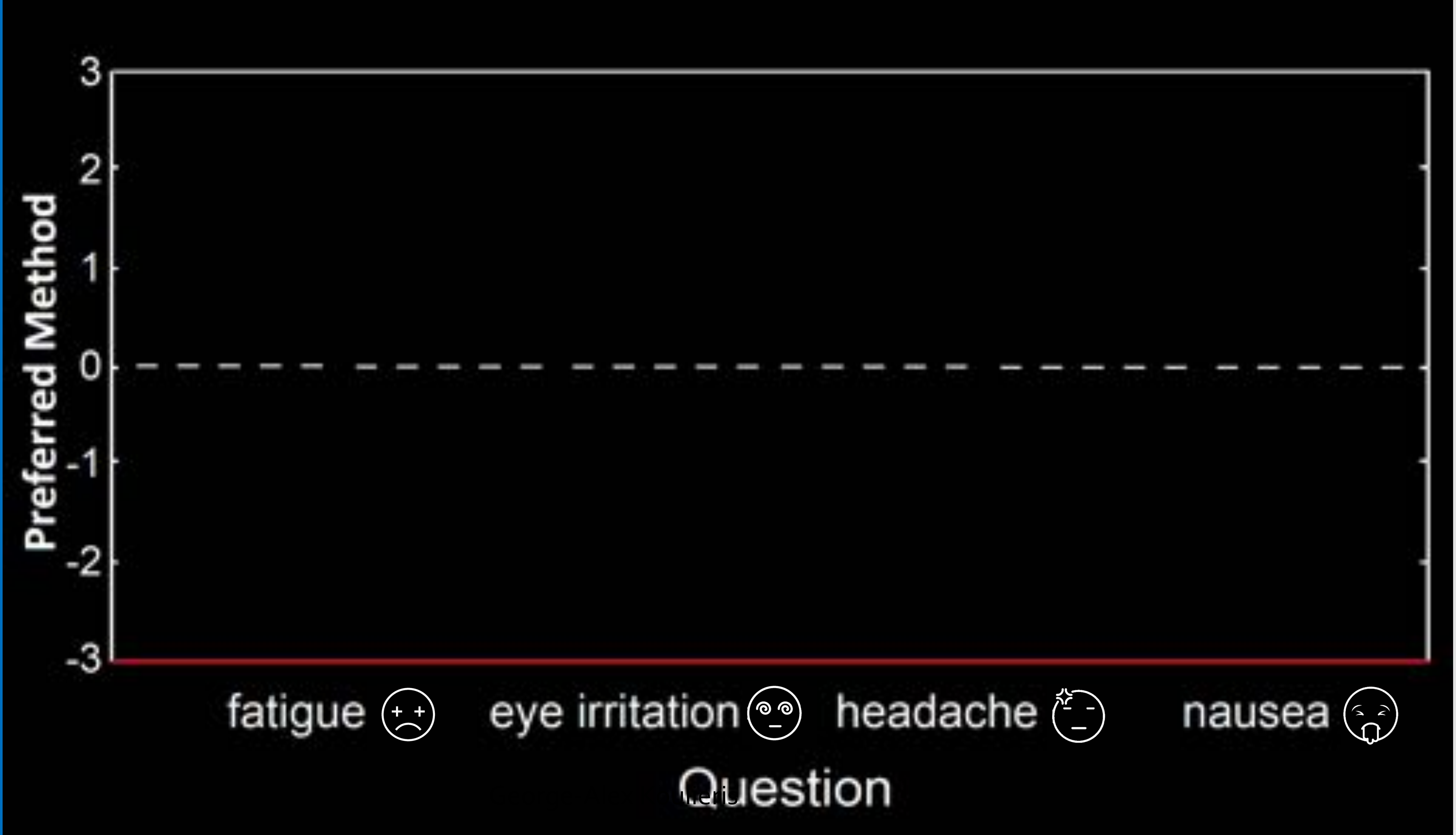
1. Changing-lens configuration → most comfortable
2. Monovision configuration → least comfortable

Discomfort study

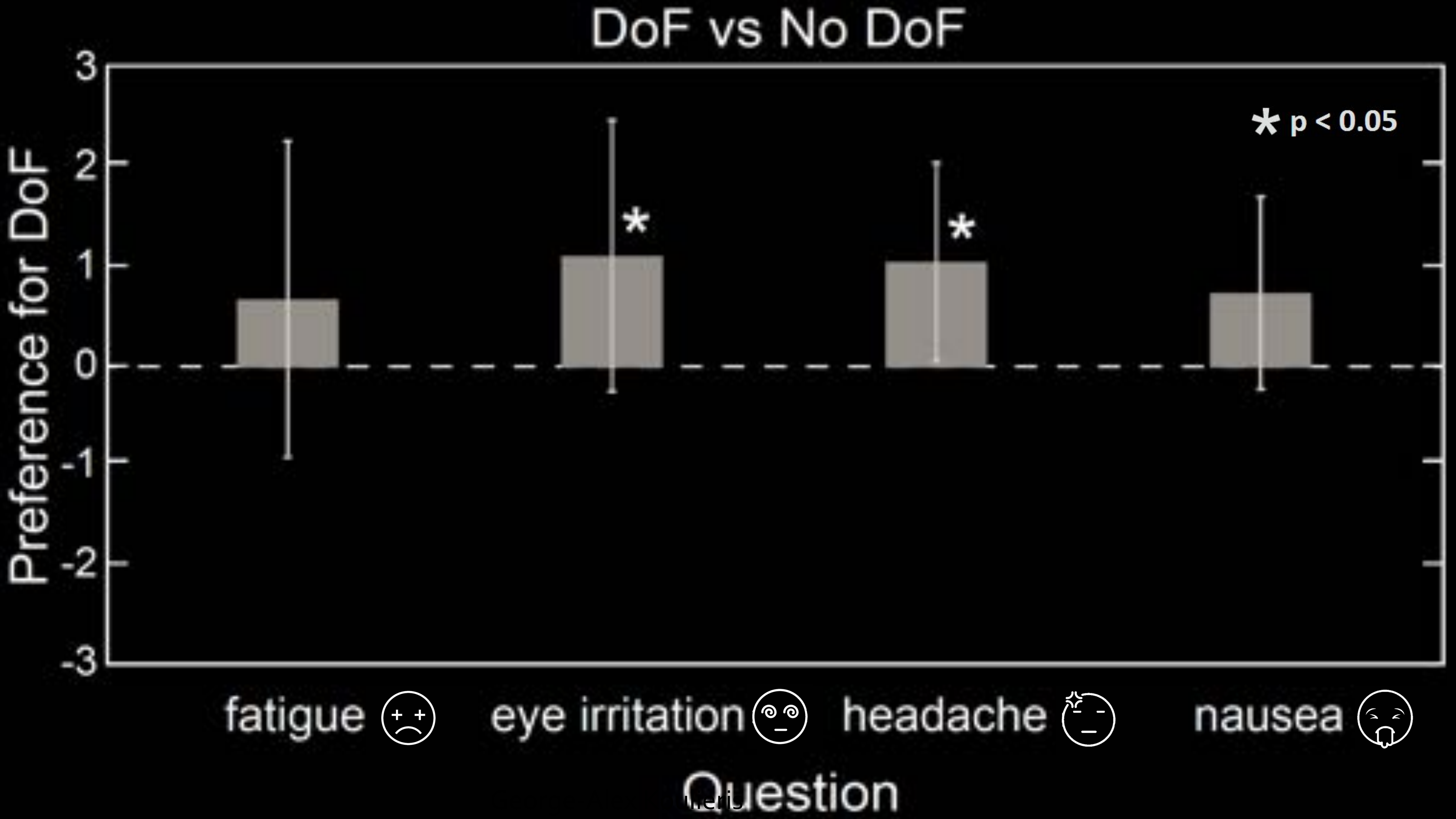
- Pair-wise comparison of display configurations
- Detection of the tumbling-E ensured correct fixation
- 30-minute trials !
- 16 subjects in each pairwise comparison

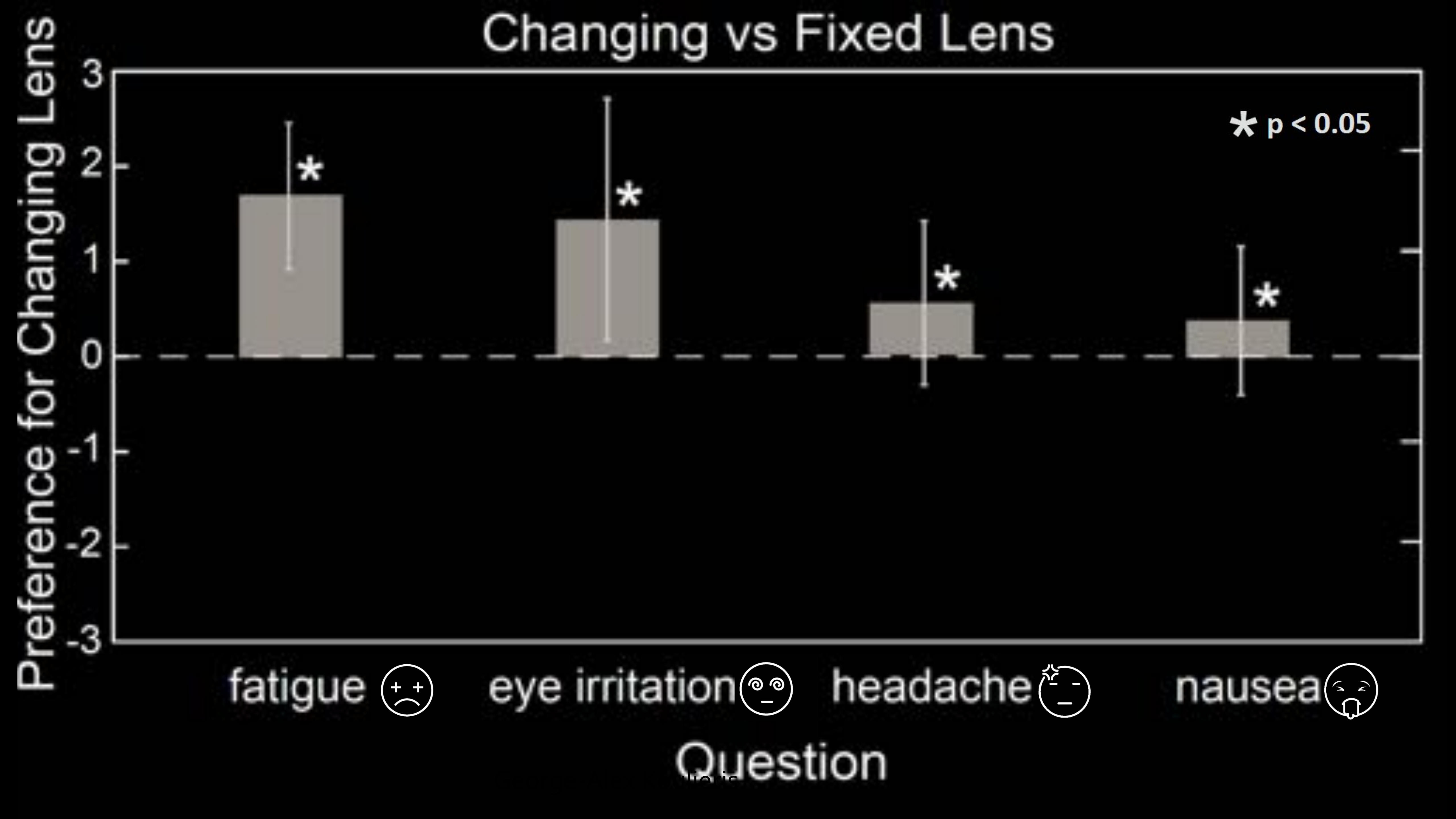

(the tumbling-E was much less discernible during the experiment)

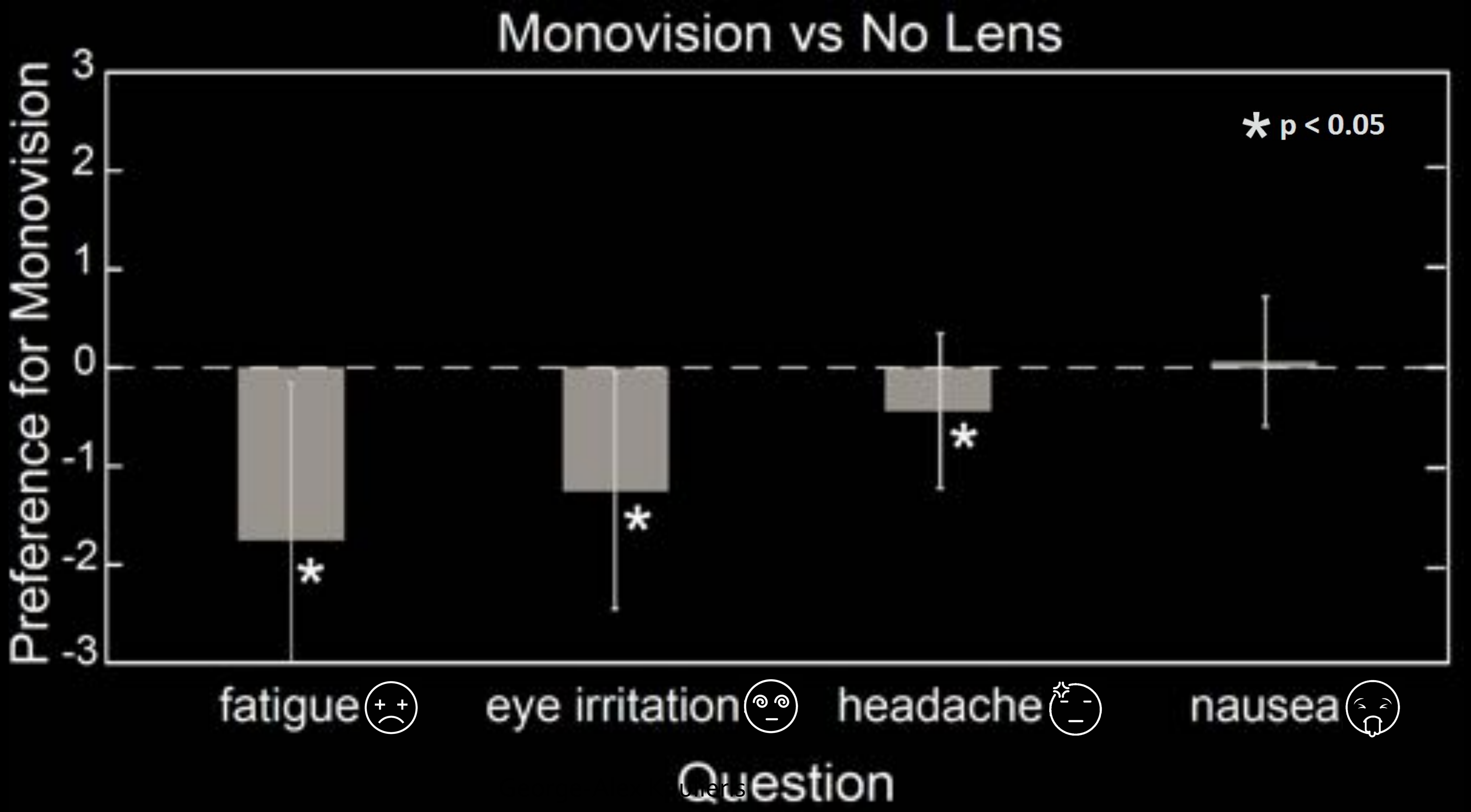

Preferred Method
3
2
1
0
-1
-2
-3
fatigue
eye irritation
headache
nausea
Question



3
2
1
0
-1
-2
-3
Preferred Method
fatigue
eye irritation
headache
nausea
Question


DoF vs No DoF
* p < 0.05
Preference for DoF
3
2
1
0
-1
-2
-3
fatigue
eye irritation
headache
nausea
Question


Changing vs Fixed Lens
Preference for Changing Lens
3
2
1
0
-1
-2
-3
* p < 0.05
fatigue
eye irritation
headache
nausea
Question

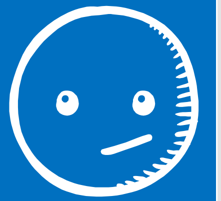

Monovision vs No Lens
Preference for Monovision
3
2
1
0
-1
-2
-3
* p < 0.05
*
*
*
fatigue
eye irritation
headache
nausea
Question

Summary

Monovision

X Does not drive accommodation correctly

! Causes more discomfort than standard HMDs!



Gaze-Contingent DoF blur

X Does not drive accommodation – as expected!

✓ More comfortable than standard HMDs

Focus-Adjustable lenses

✓ Drive accommodation correctly

✓ Significantly improve comfort

Take-home points

- Accommodation must be driven by correct focus cues
- Accommodation data yielded predictions about comfort
- Discomfort study results consistent with predictions
- Ground discomfort studies on objective measurements

Koulieris, G. A., Bui, B., Banks, M. S., & Drettakis, G. (2017). Accommodation and comfort in head-mounted displays. *ACM Transactions on Graphics (TOG)*, *36*(4), 87.

Thank you

https://vrdisplays.github.io/ieeevr2018/

george.koulieris@inria.fr

Schedule

- 9:00 – 9:30: Introduction
- 9:30 – 10:15: Multi-focal displays
- 10:30 - 11:00: Coffee break
- 11:00 – 11:50: Near-eye varifocal AR
- 12:00 - 14:00: Lunch
- 14:00 – 14:40: HDR-enabled displays
- 14:45 – 15:25: Gaze-aware displays
- 15:30 – 16:00: Coffee break
- 16:00 – 16:50: Motion-aware displays
- 17:00 – 17:20: Panel