Cutting-Edge VR/AR Display Technologies

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

George-Alex Koulieris

Kaan Akşit

Christian Richardt

Rafał Mantiuk

Durham University

NVIDIA

University of Bath

University of Cambridge

Course 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

Speakers

- Kaan Akşit, NVIDIA, USA
- Rafał Mantiuk, University of Cambridge, UK
- Christian Richardt, University of Bath, UK
- George-Alex Koulieris, Durham University, UK

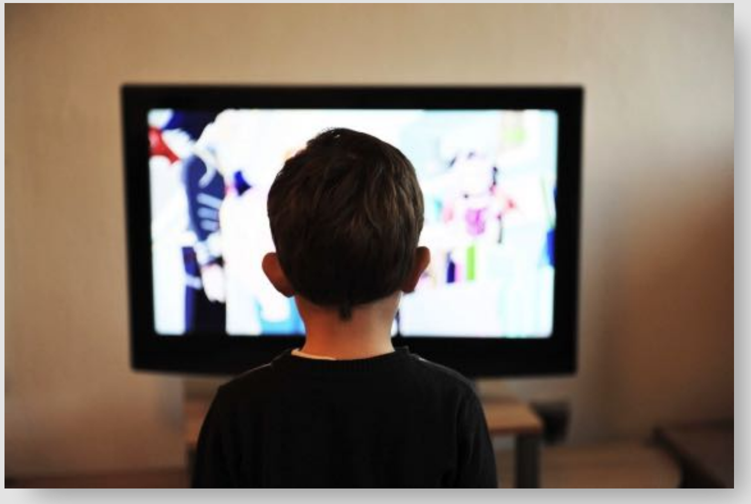
Schedule

Start	Topic	Speaker
14:15	Introduction	George Alex Koulieris
14:30	Multi-focal displays	George Alex Koulieris
15:05	Near-eye varifocal AR	Kaan Akşit
15:50	Coffee break	
16:00	HDR-enabled displays	Rafał Mantiuk
16:45	Motion-aware displays	Christian Richardt
17:30	Demos & Summary	All presenters

Let’s get started

A Turing test for displays

George-Alex Koulieris



Virtual, augmented, mixed reality displays

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

George-Alex Koulieris

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
- Research surge:
  SIGGRAPH, IEEE VR, ISMAR, ...
- *"A billion people in virtual reality"*
  Mark Zuckerberg

NVIDIA Google Microsoft SONY SAMSUNG Nintendo

Before this becomes commonplace…

George-Alex Koulieris

Current near-eye display challenges

George-Alex Koulieris

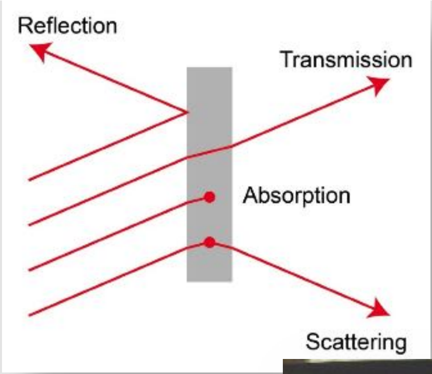
- Ergonomic / Comfort
- Visual Quality issues
- Perceptual
- Technical
- Interaction

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

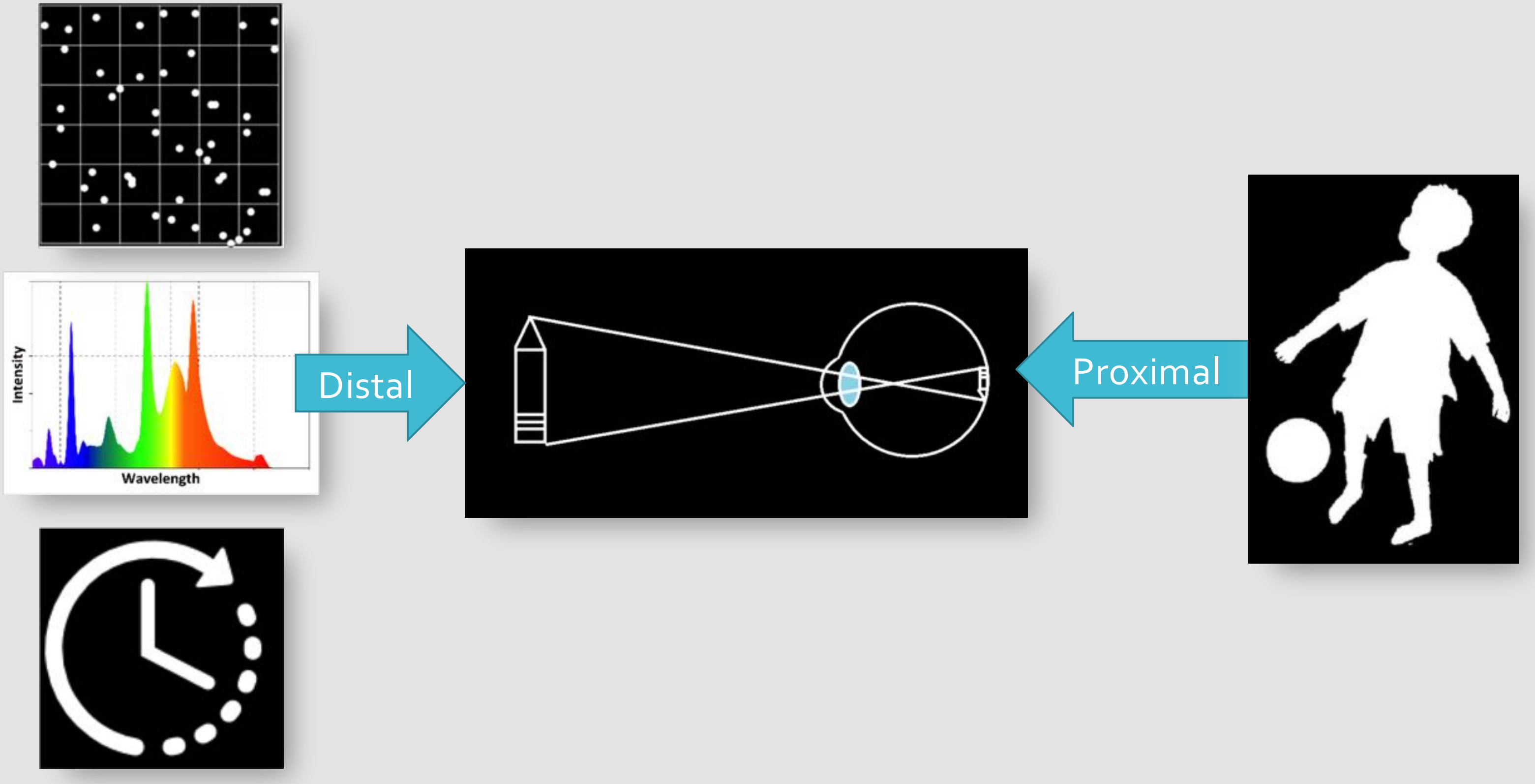
But how do we take knowledge from visual perception into account?

Human vision



George-Alex Koulieris

What visual perception does



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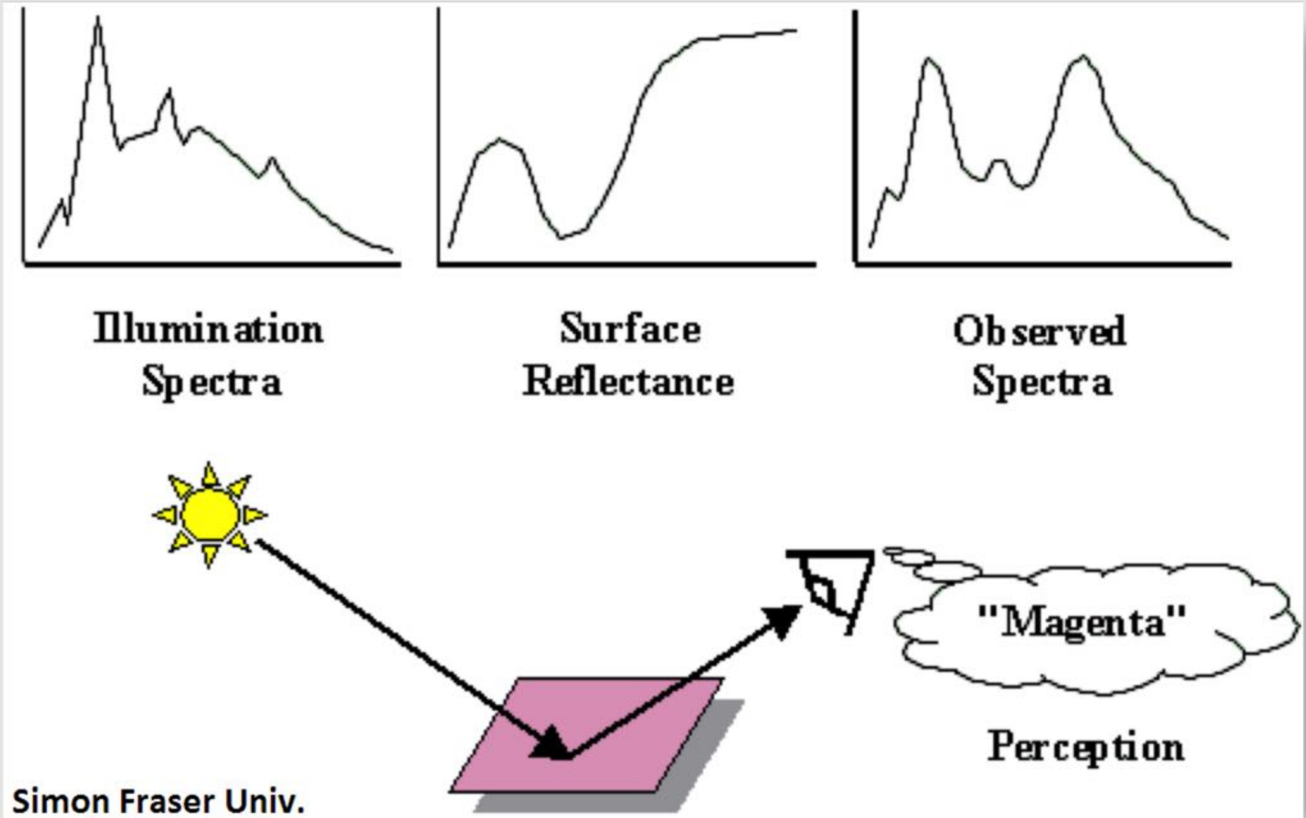
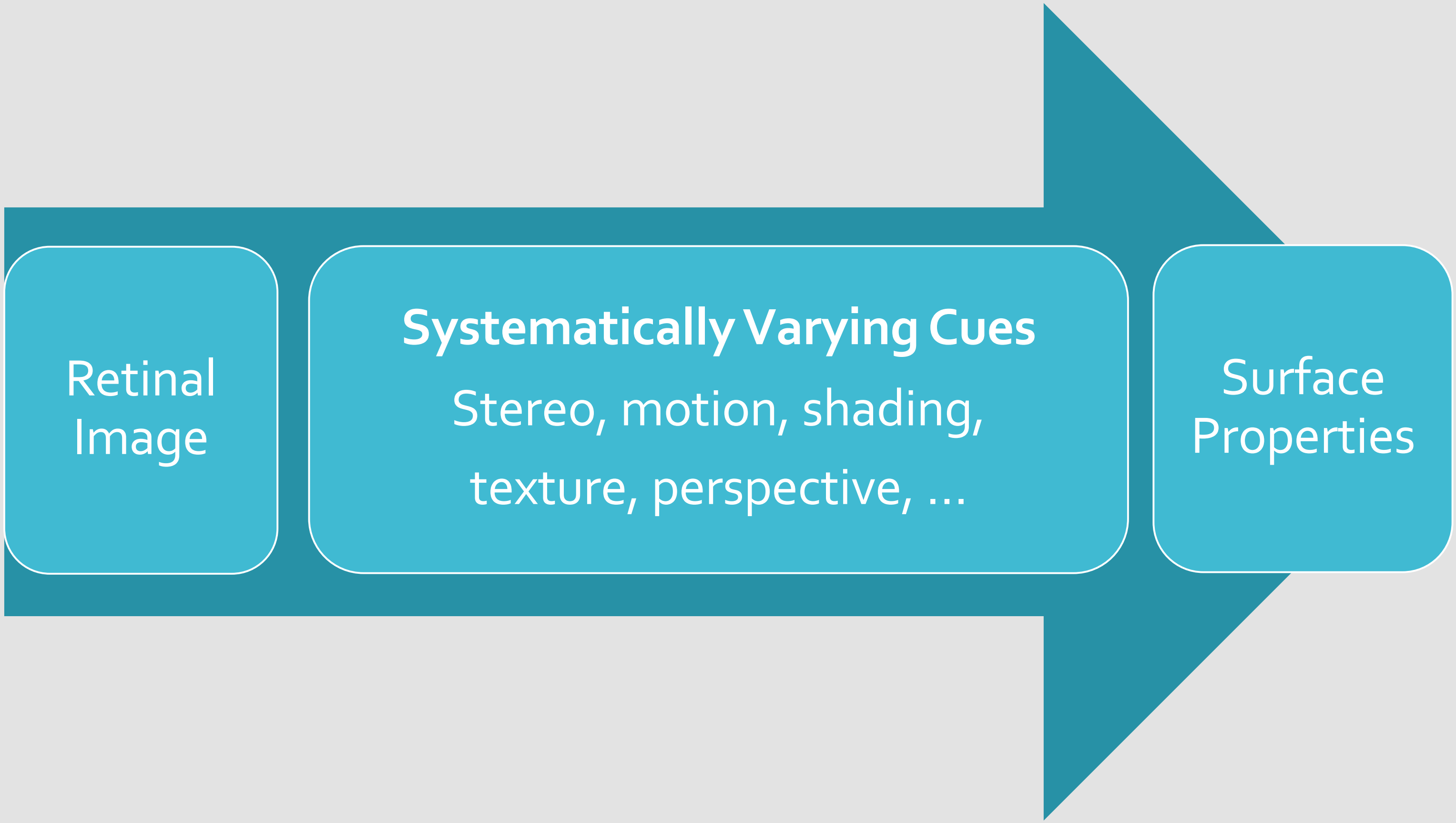
Proximal → Distal: A difficult, inverse problem



#oilylegs

Visual perception and visual cues



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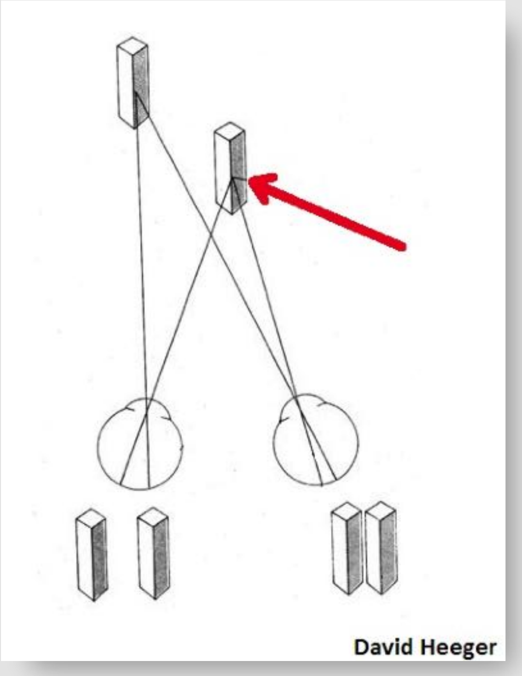
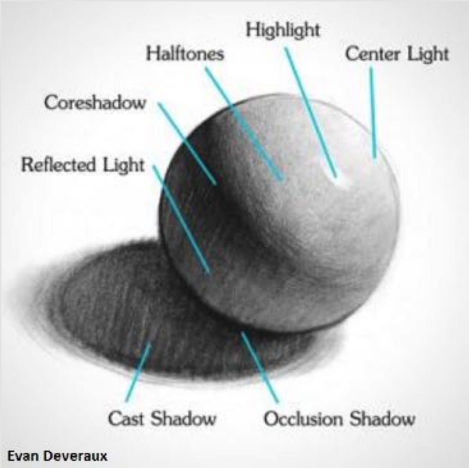
Examples of visual cues

- 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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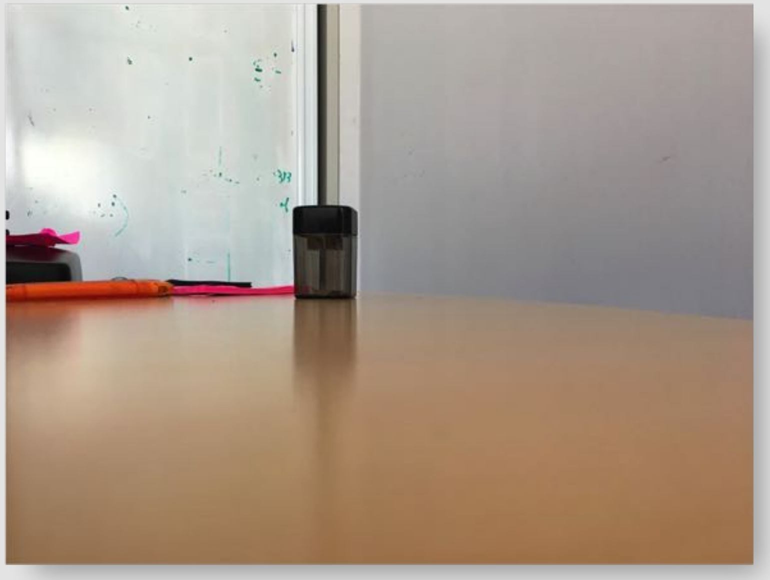
Cue integration



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

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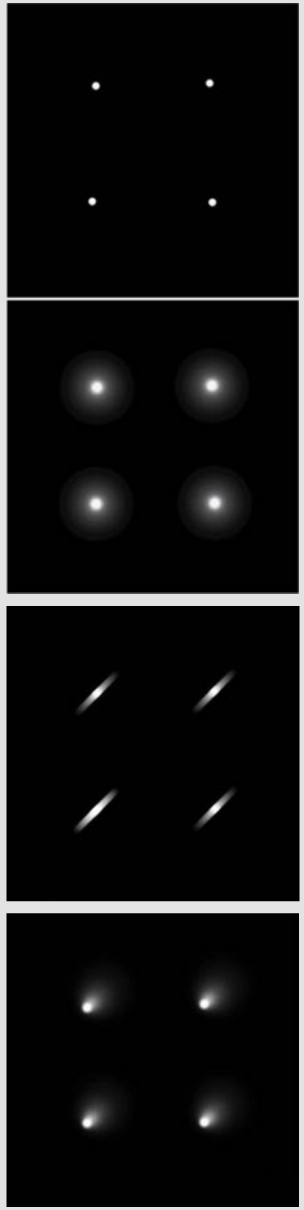
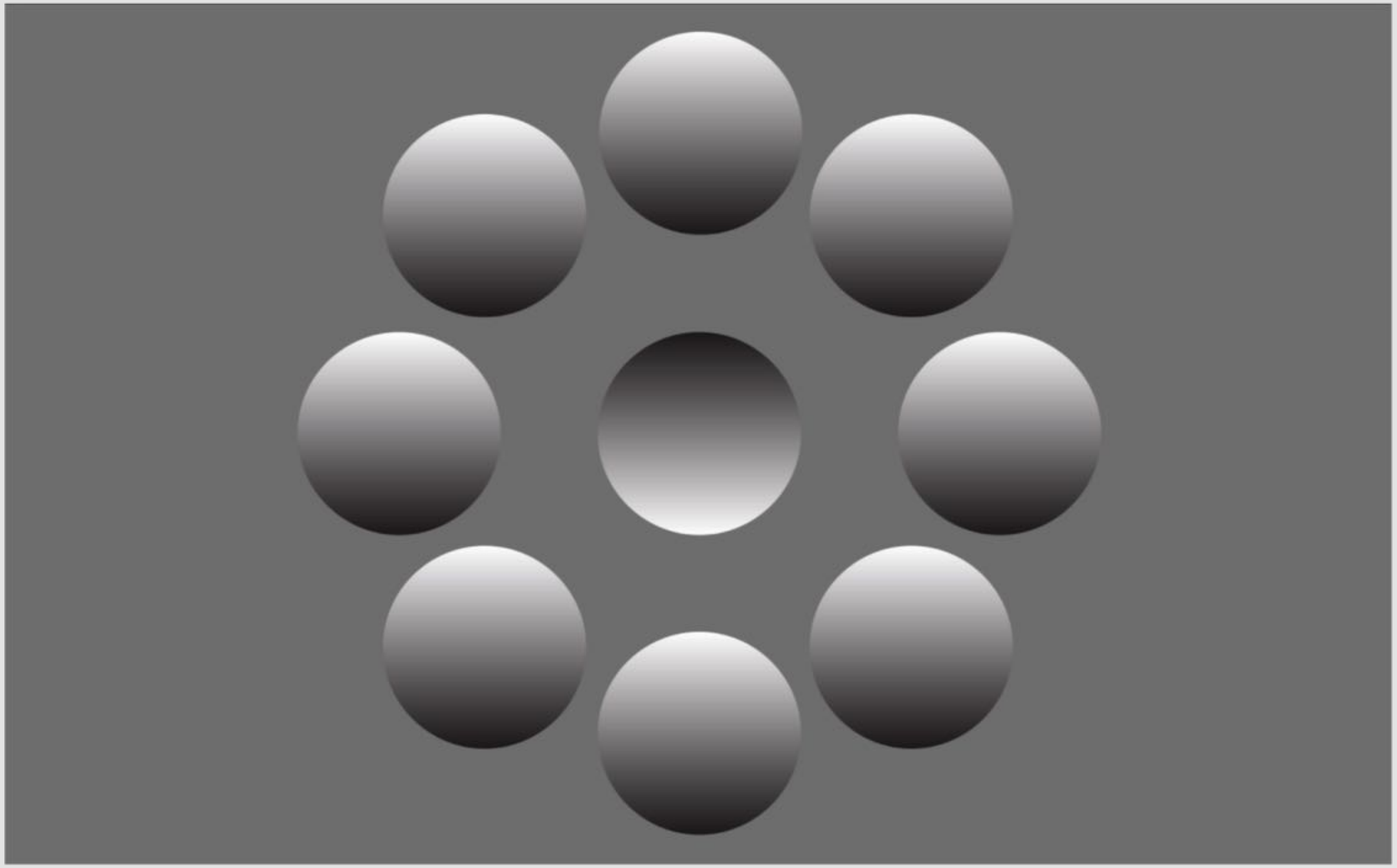
Cue conflicts

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



Fun fact: conflicting cues



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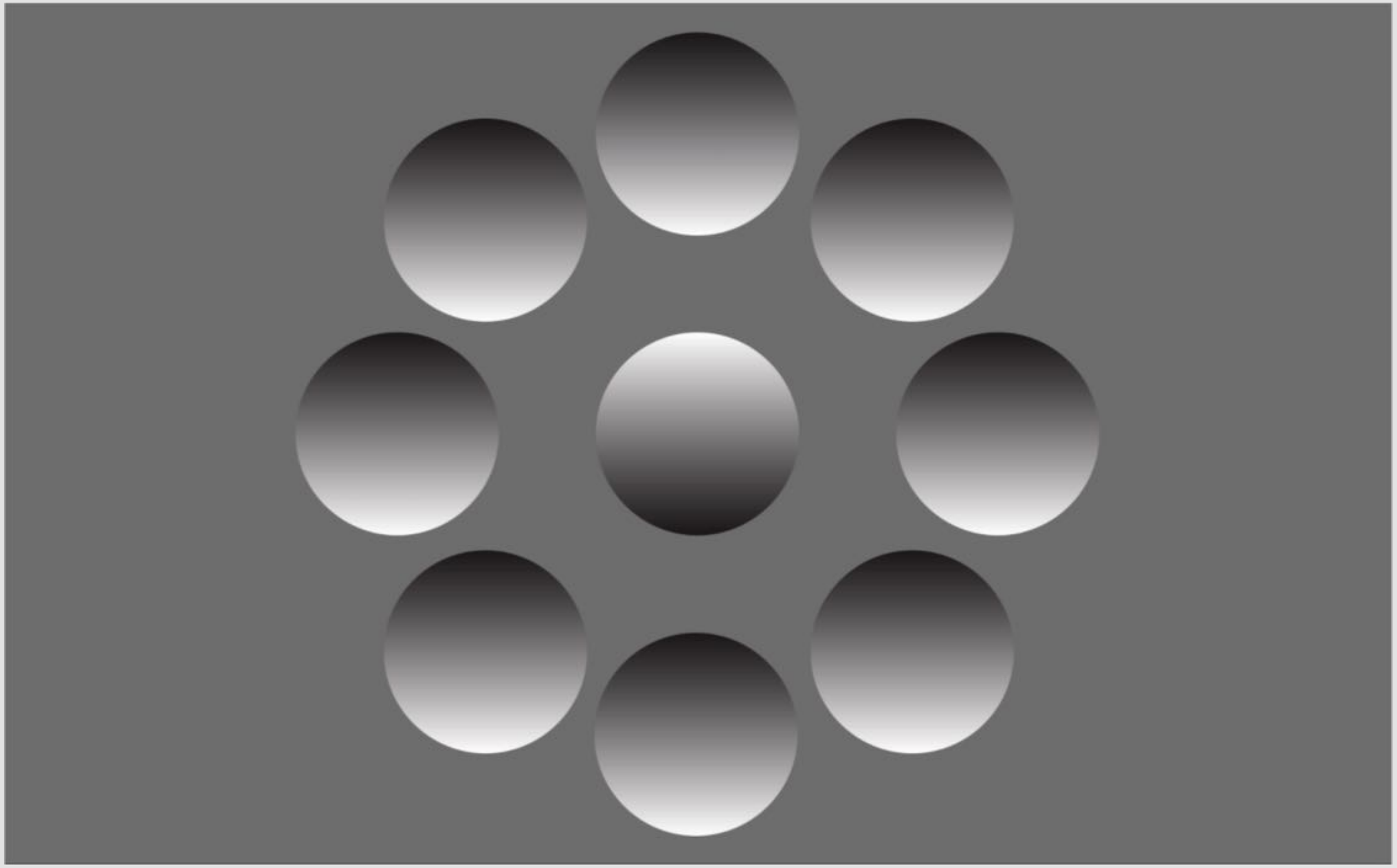
Fun fact: conflicting cues



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How do we study visual perception?

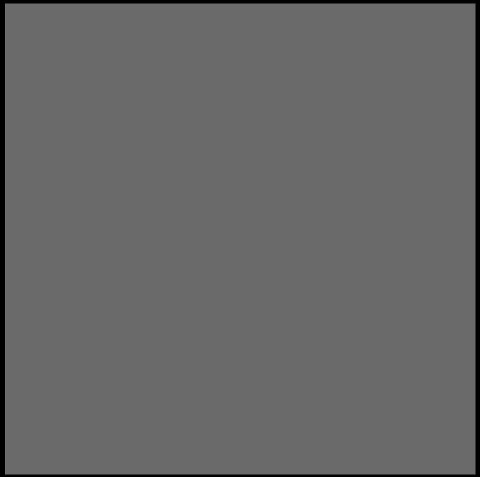
Psychophysical methods of study (1)

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

Example: luminance threshold detection



- 200ms patch
- PRESENT / ABSENT ?

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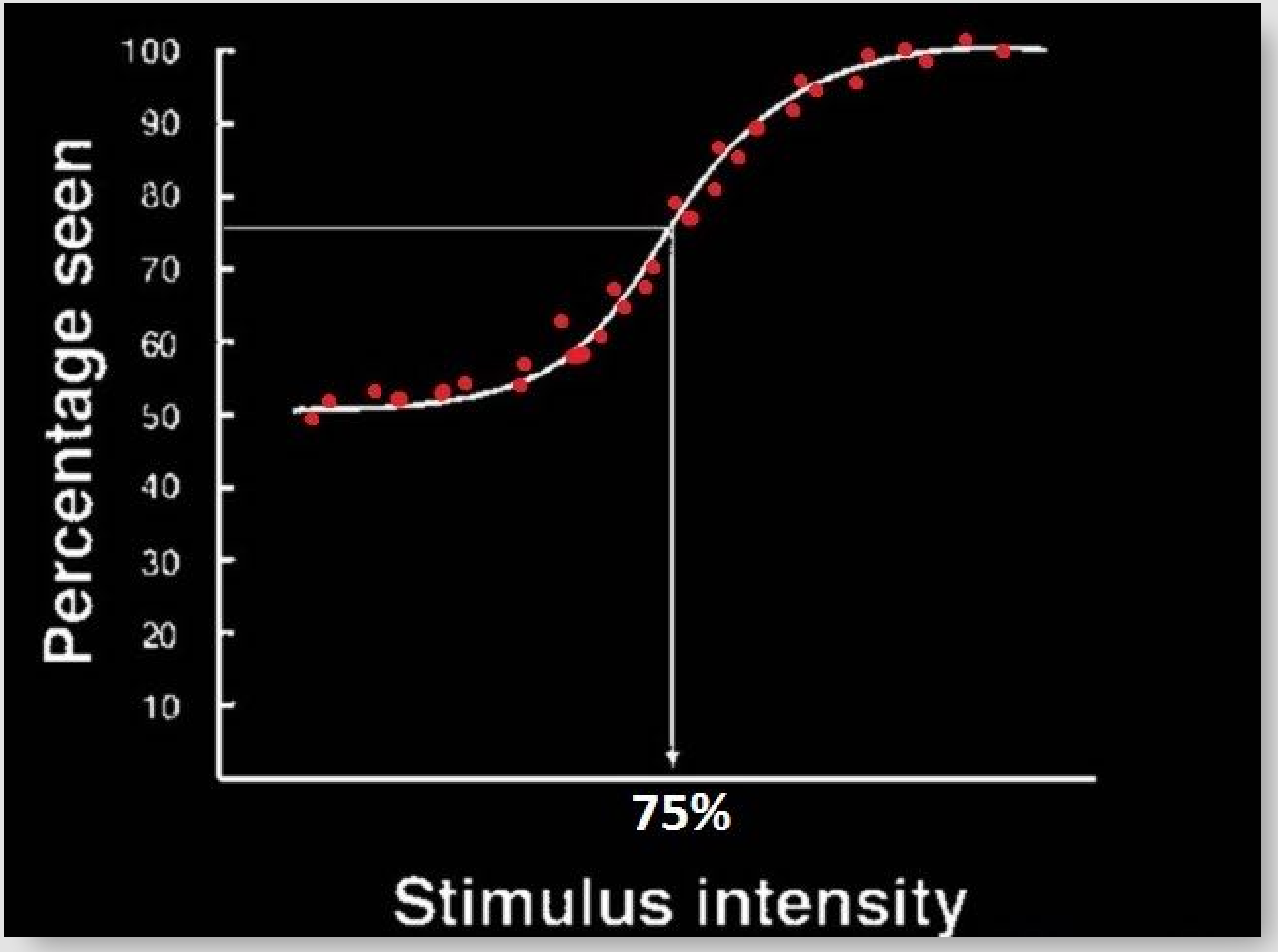
Psychometric functions



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

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Course take-aways

Course take-aways (1)

Q: Why multifocal displays?

Q: Why varifocal AR?

A: Eyes evolved to focus on objects at different distances.

Kaan Akşit

NVIDIA

George Alex Koulieris

Durham University

Course take-aways (2)

Q: Why HDR-enabled displays?

A: Relates to the sensitivity of the eyes.

Rafał Mantiuk

UNIVERSITY OF CAMBRIDGE

Course take-aways (3)

Q: Why motion-aware displays?

A: Eyes attached on moving bodies.

Christian Richardt

UNIVERSITY OF BATH

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

SIGGRAPH ASIA 2018 TOKYO

George Alex Koulieris

Multi-focal Displays

SIGGRAPH Asia Course on Cutting-Edge VR/AR Display Technologies

Durham University

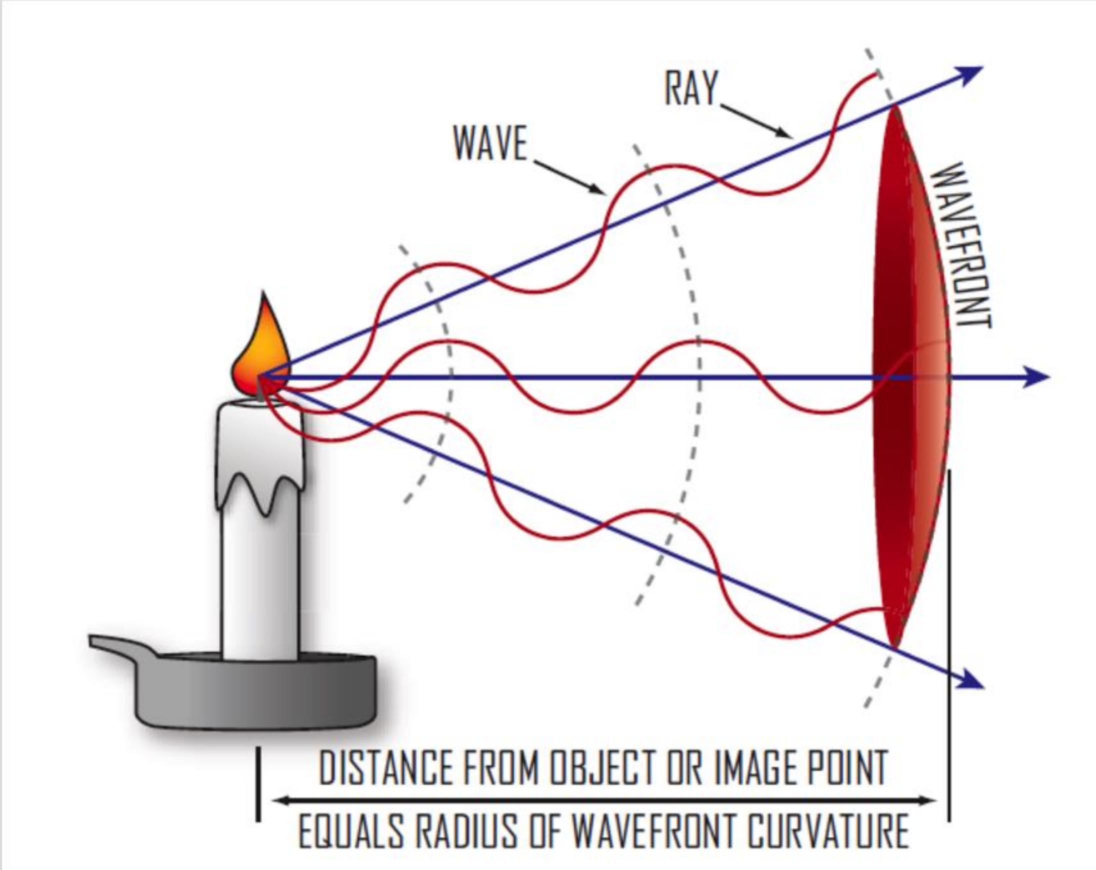
koulieris.com
GeorgeKoulieris

At a glance

- Part 1: (*very*) basic optics, human eye, accommodation, VA conflict, discomfort
- Part 2: multi-focal display technologies

Part 1:
The basics

Light wave-front



Charle Laas

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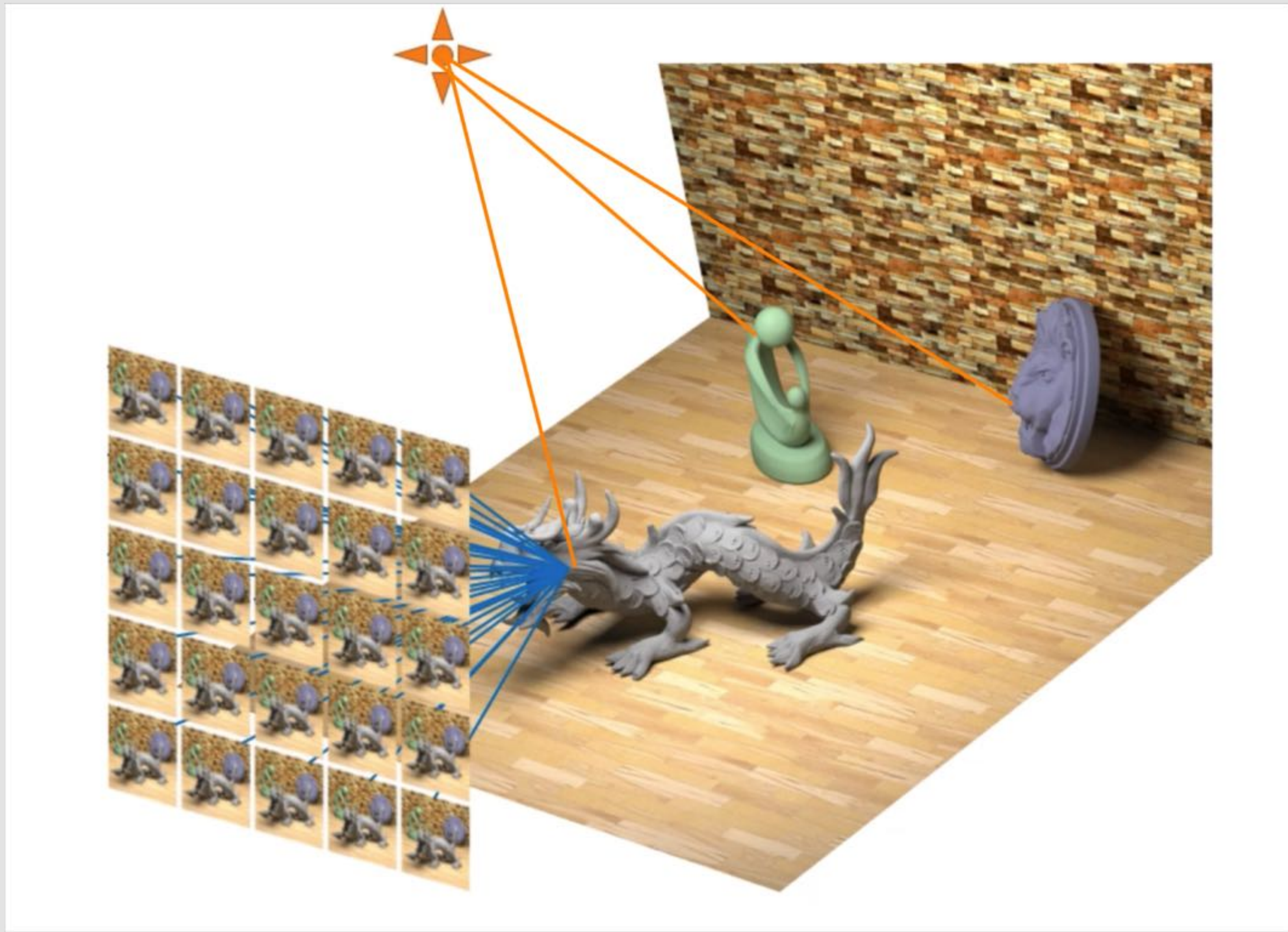
Natural light fields



Adapted from Mihara, 2016

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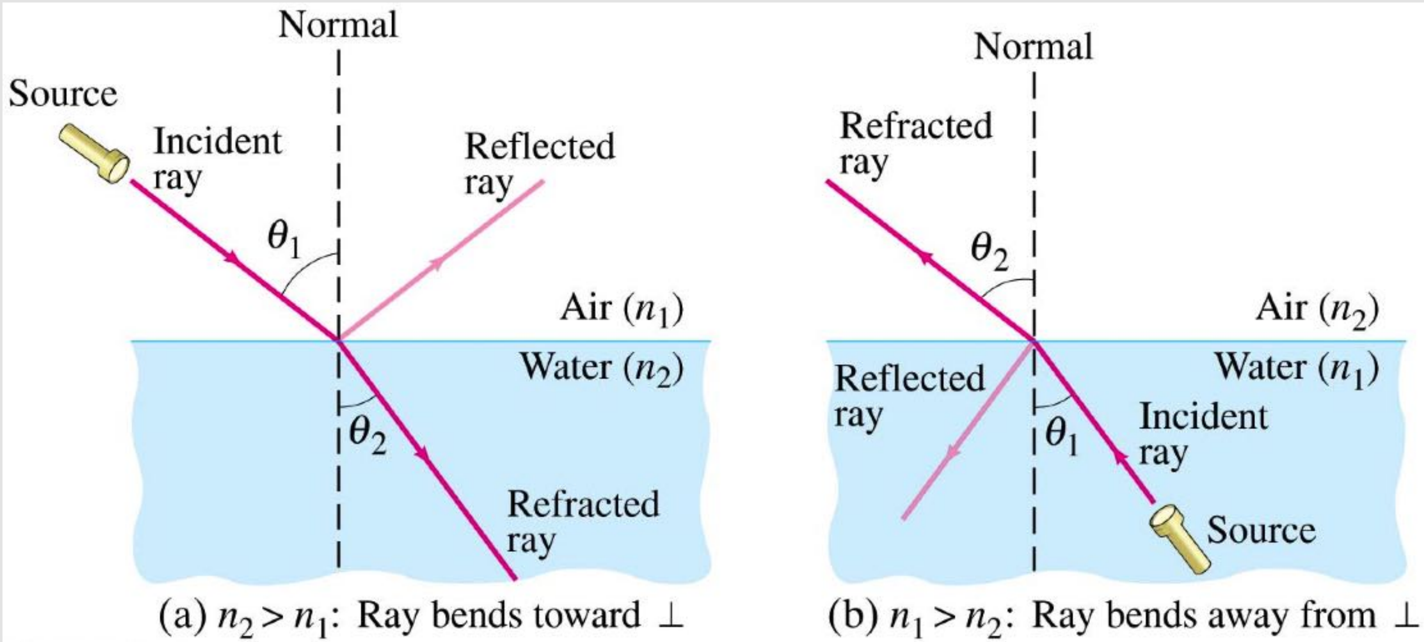
Refraction: Snell's law



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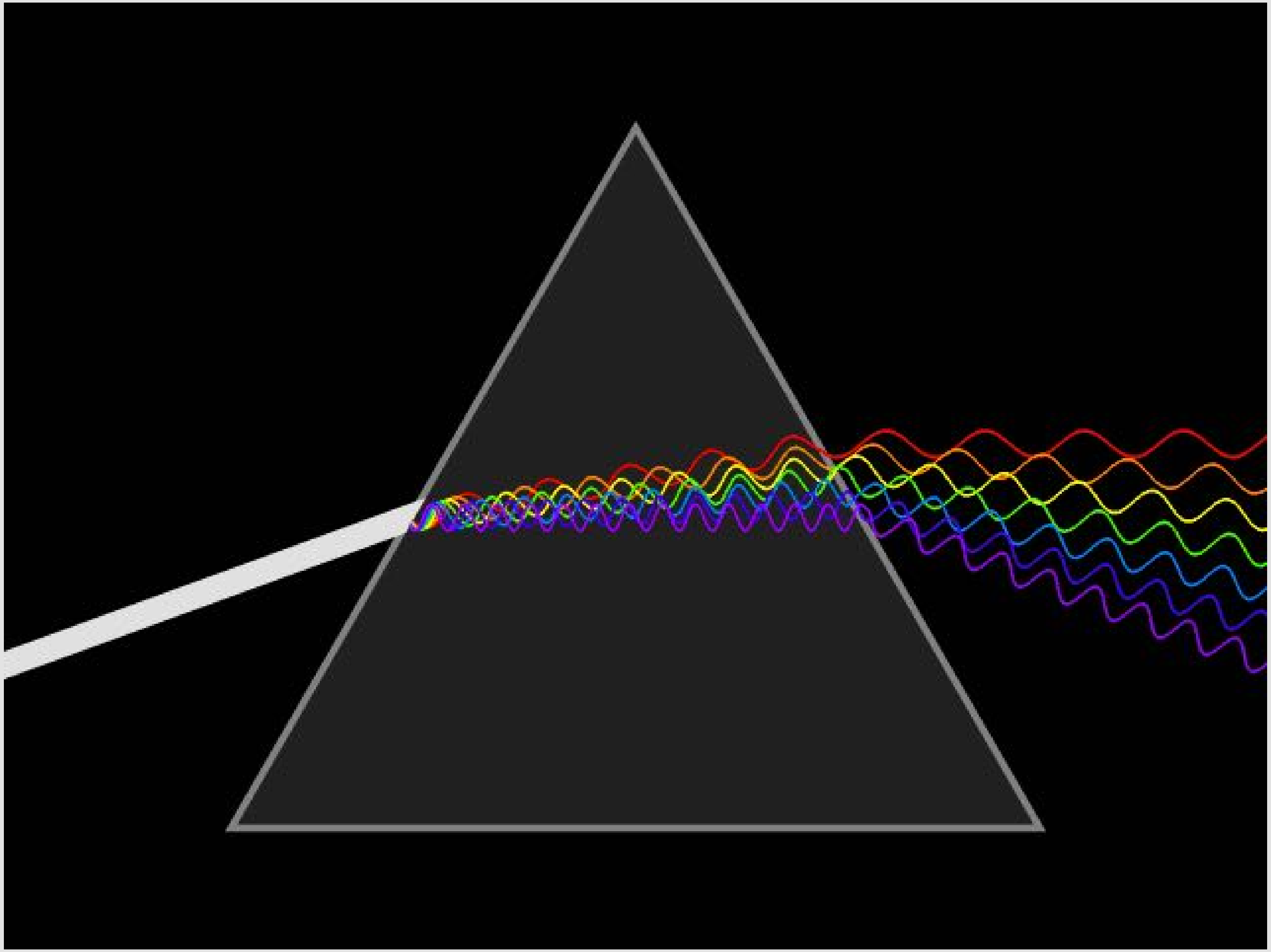
Wavelength dependent bending



Lucas Barbosa

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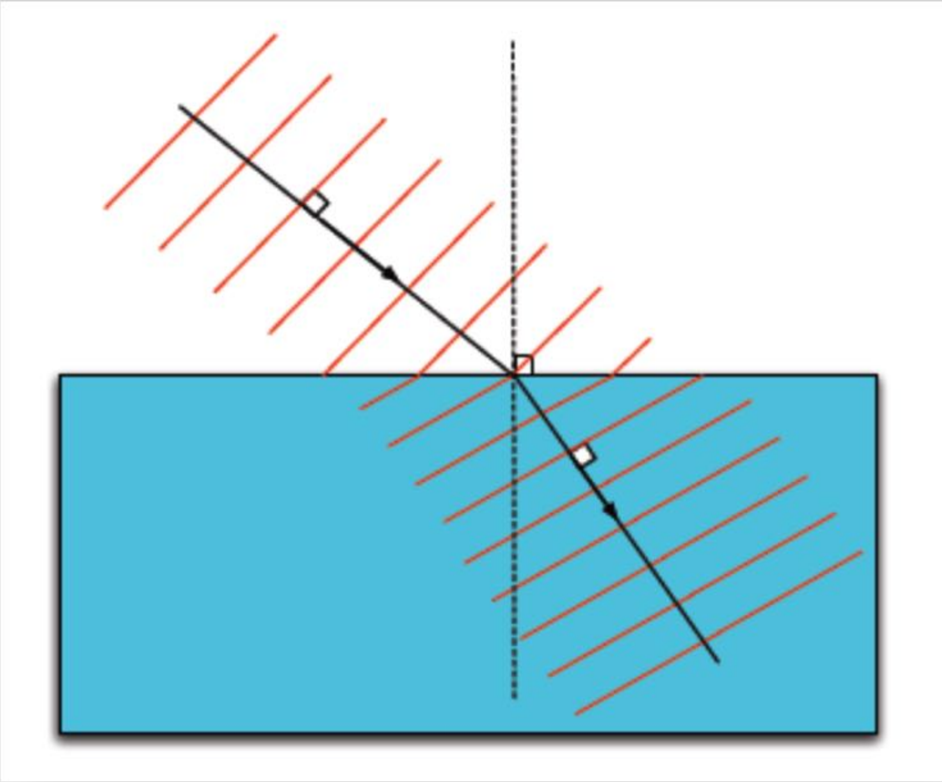
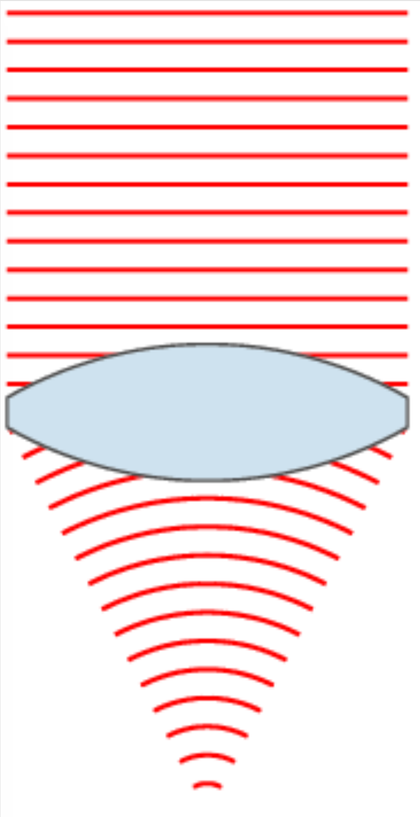
Light wave-front interacting with a lens



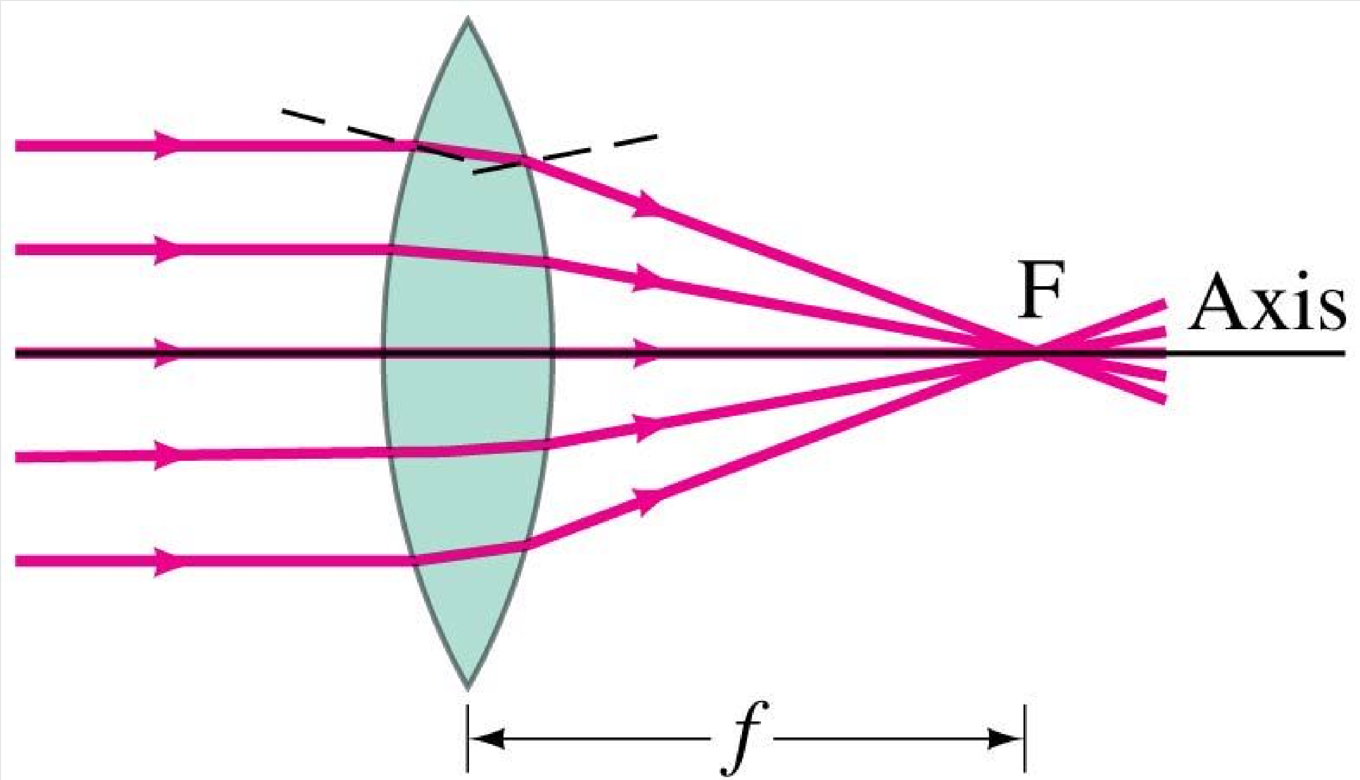
Libretexts



Oleg Alexandrov

George-Alex Koulieris

Convex thin lenses



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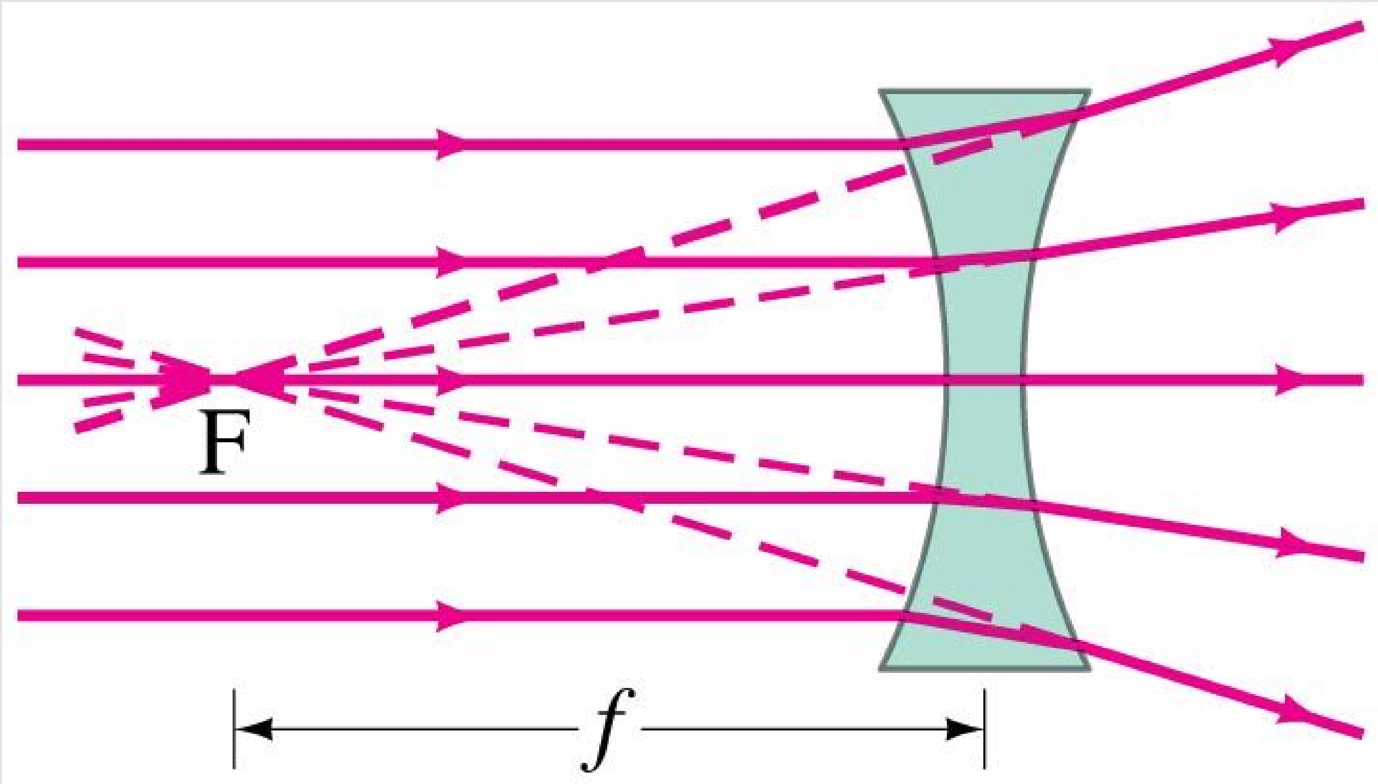
Concave thin lenses



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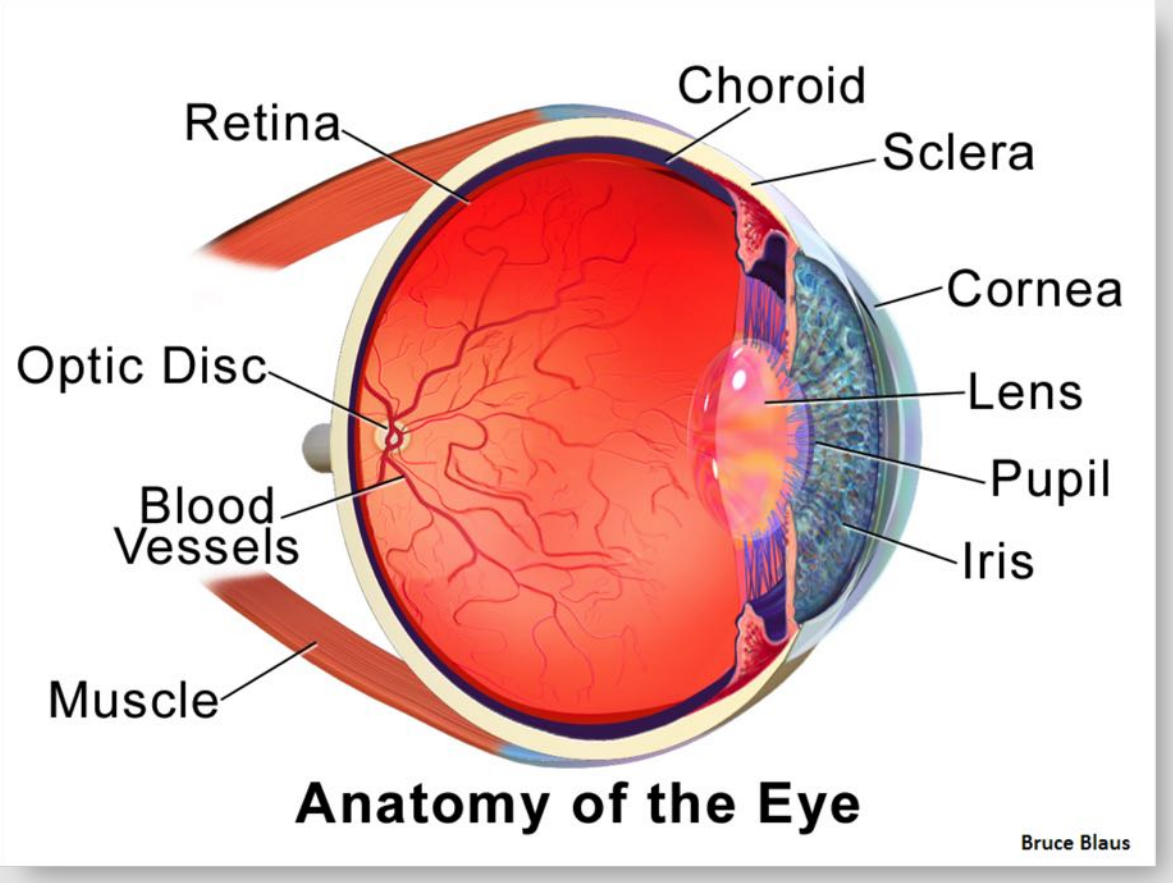
Dioptres

- 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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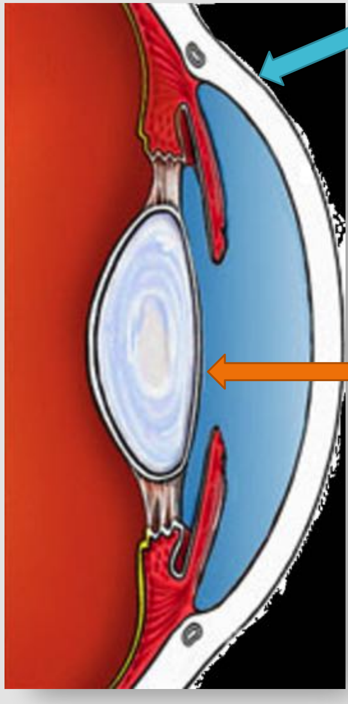
Two lenses in the eye



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

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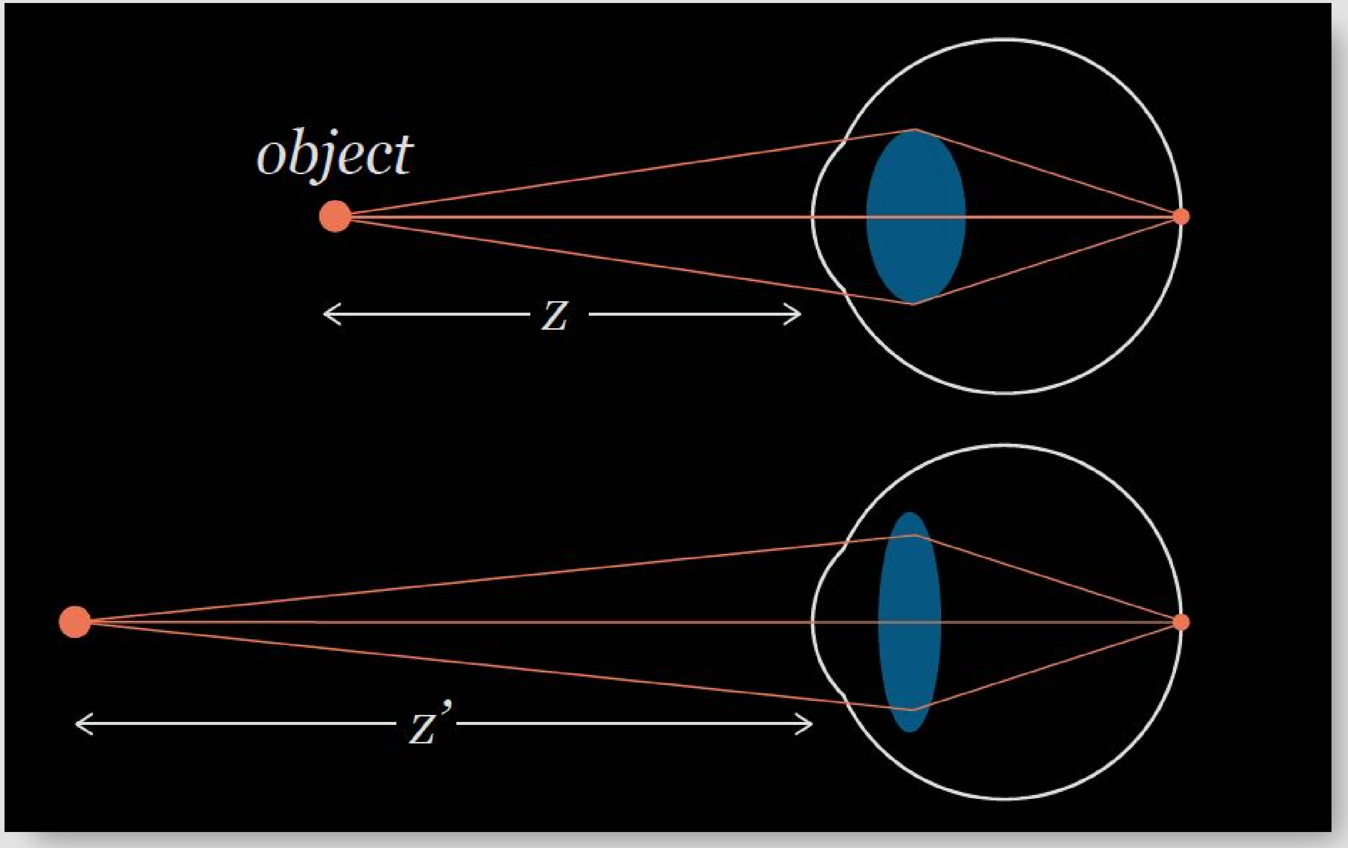
Accommodation



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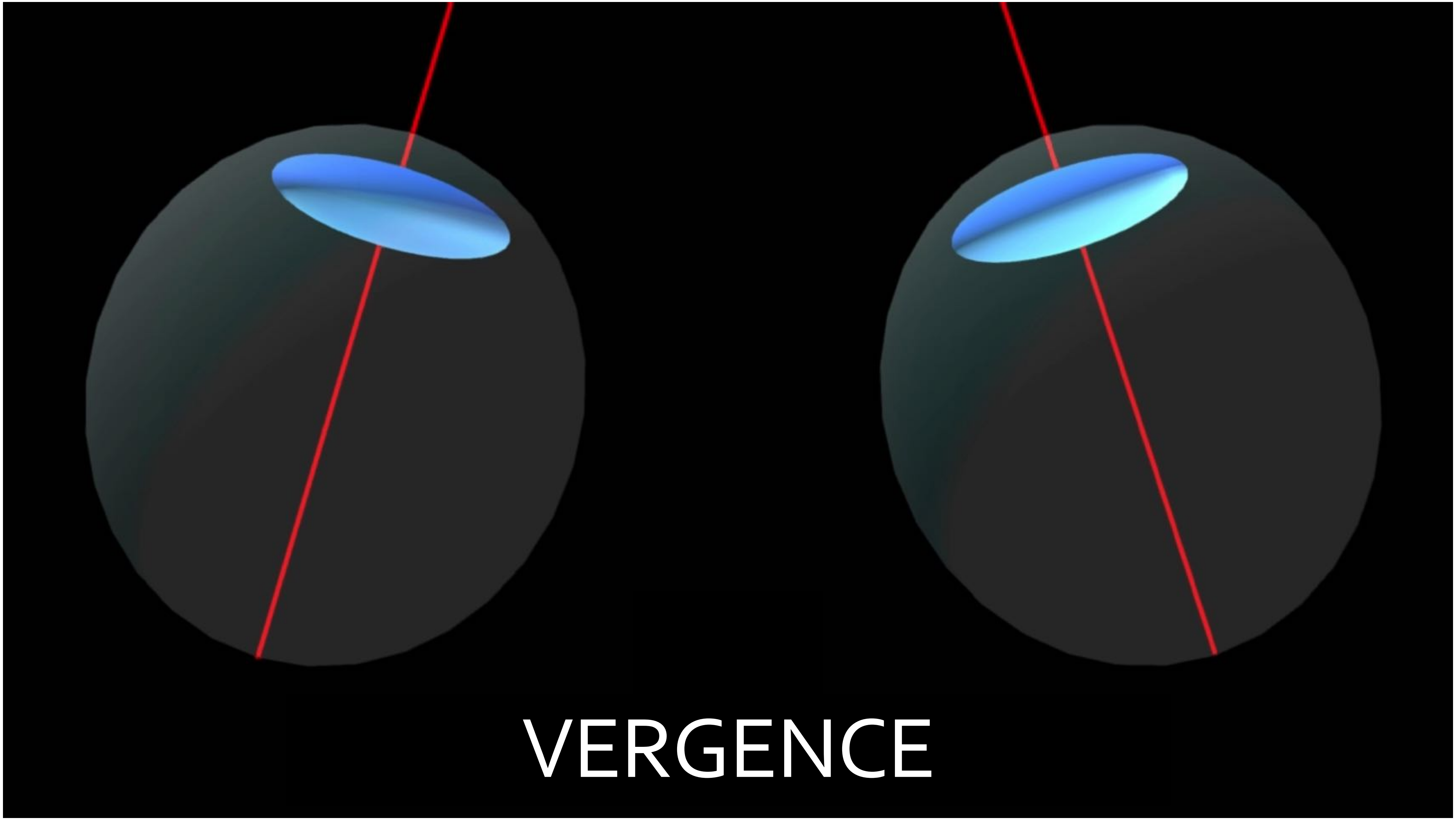
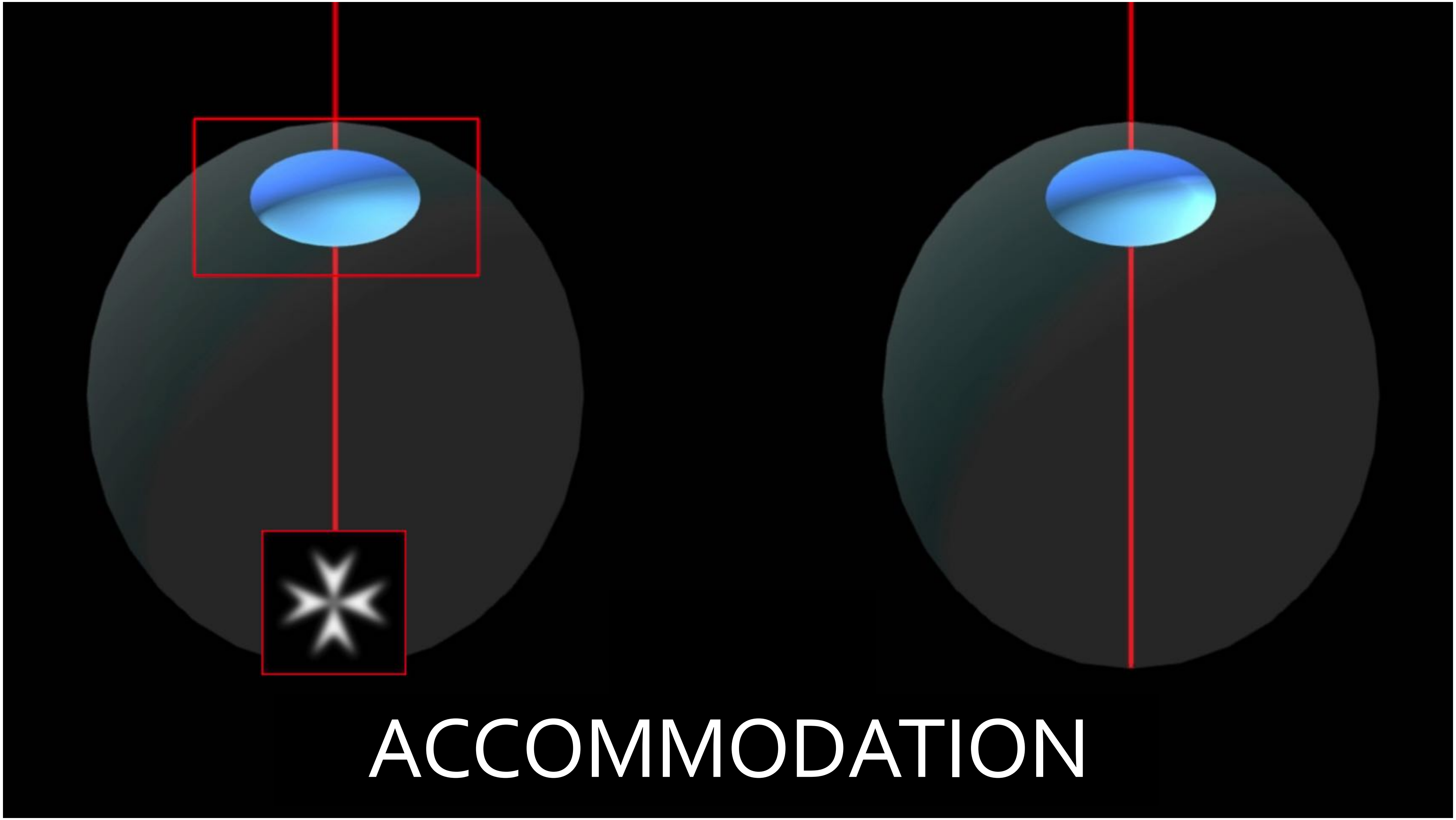
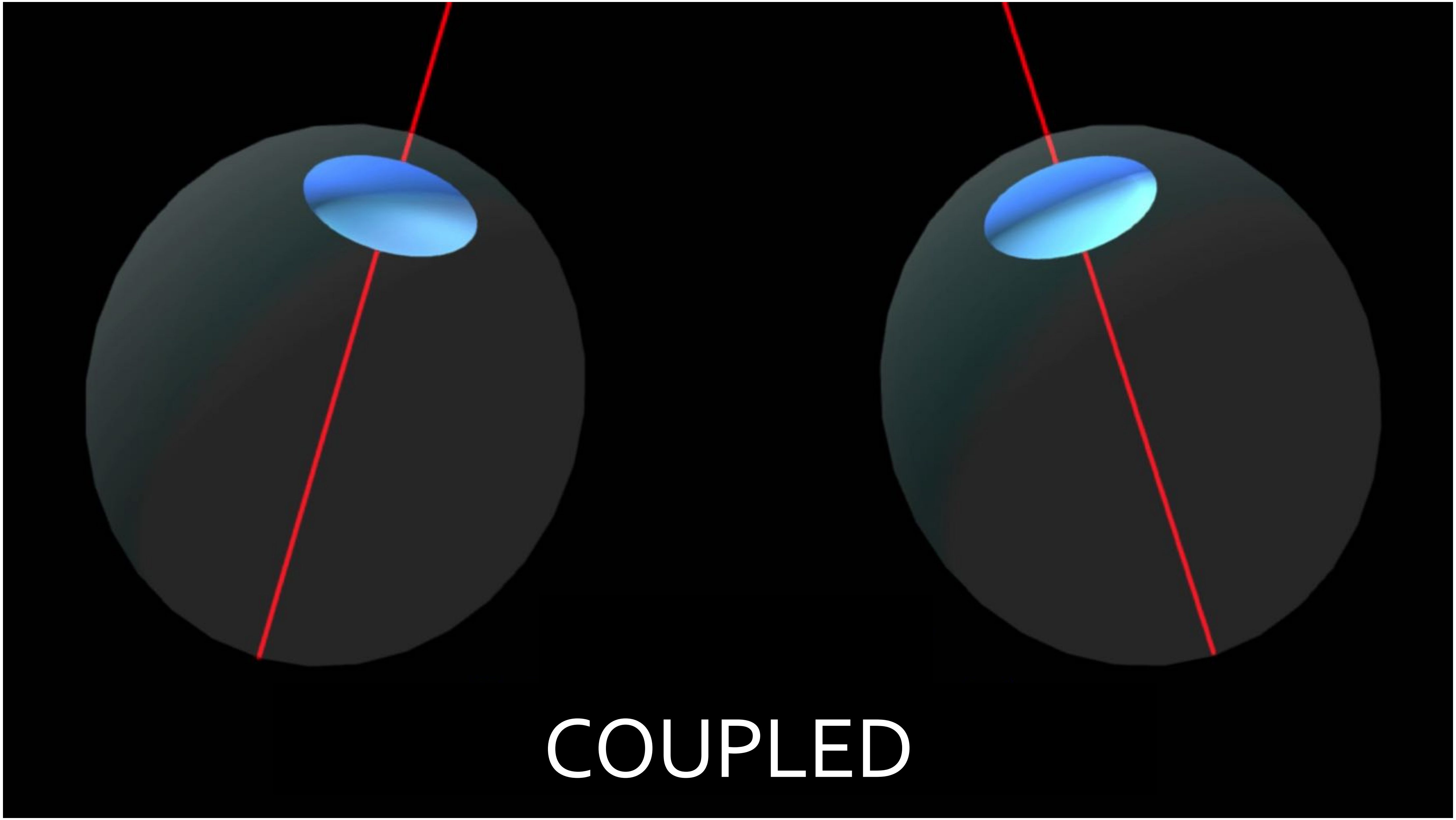
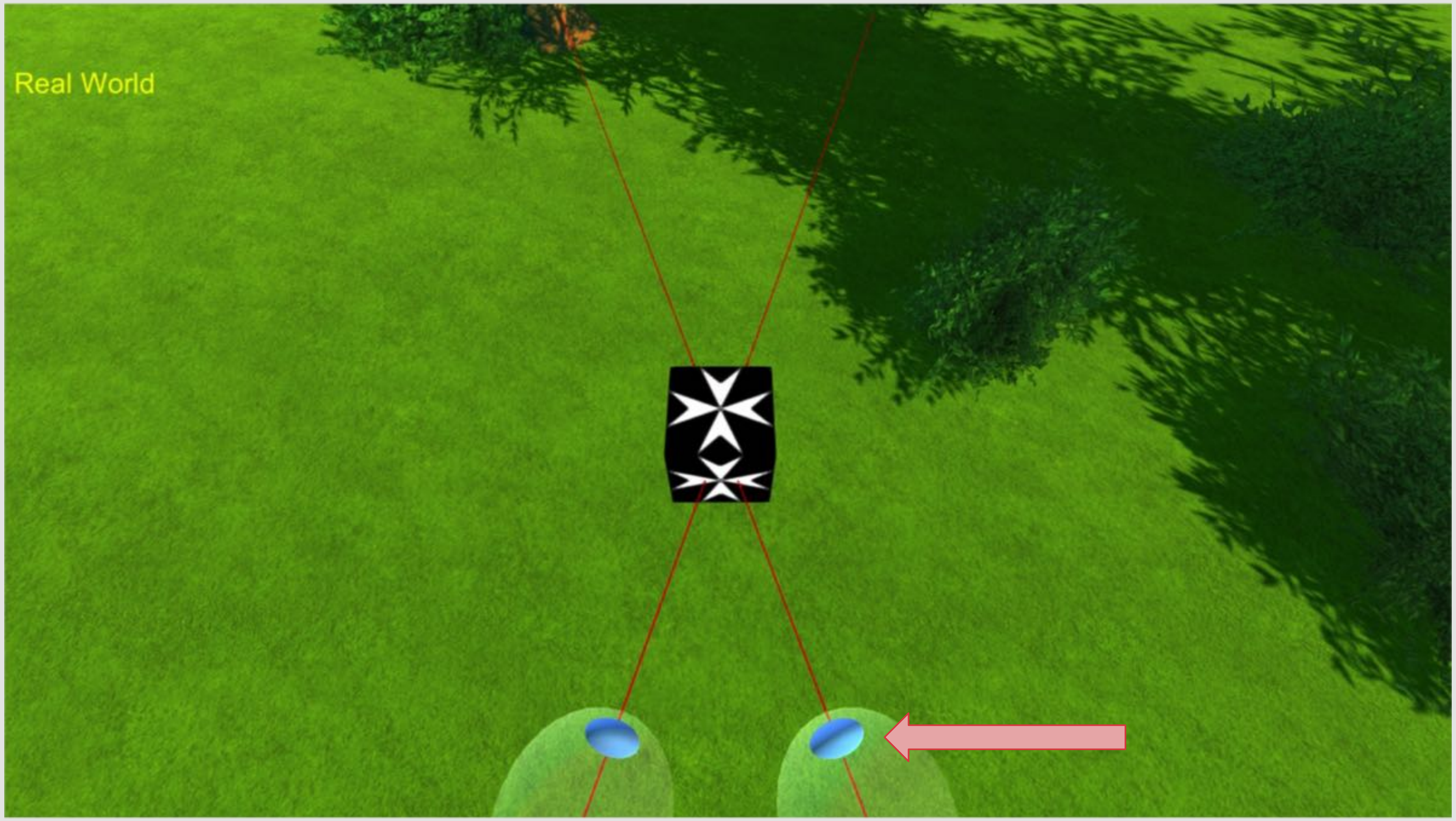
Now let us see how all this relate to a major source of discomfort in VR/AR


VERGENCE


ACCOMMODATION


COUPLED

Vergence and accommodation in the real world



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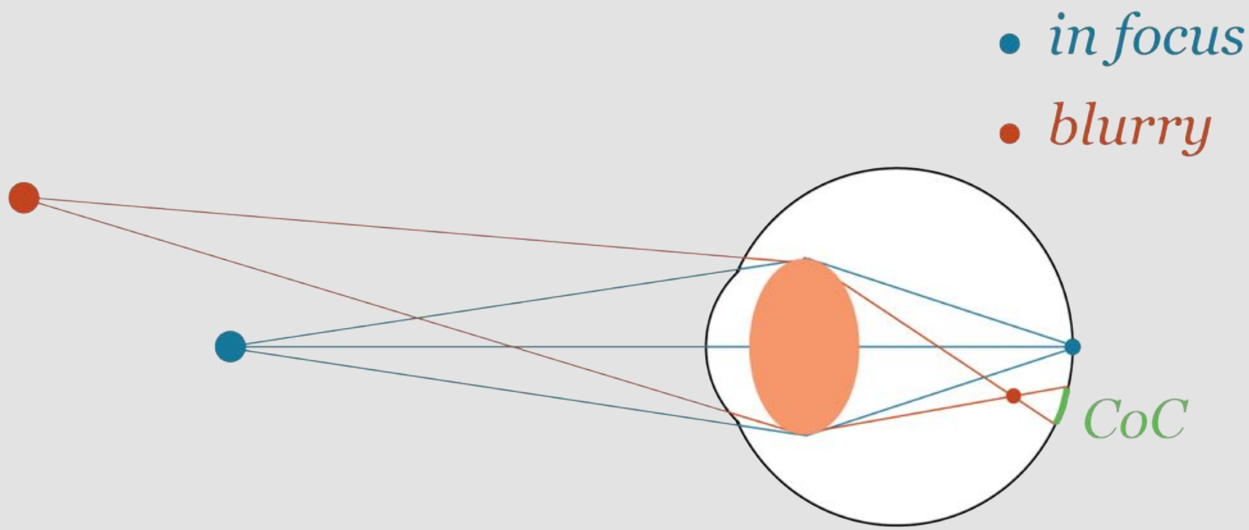
Blur in the real world



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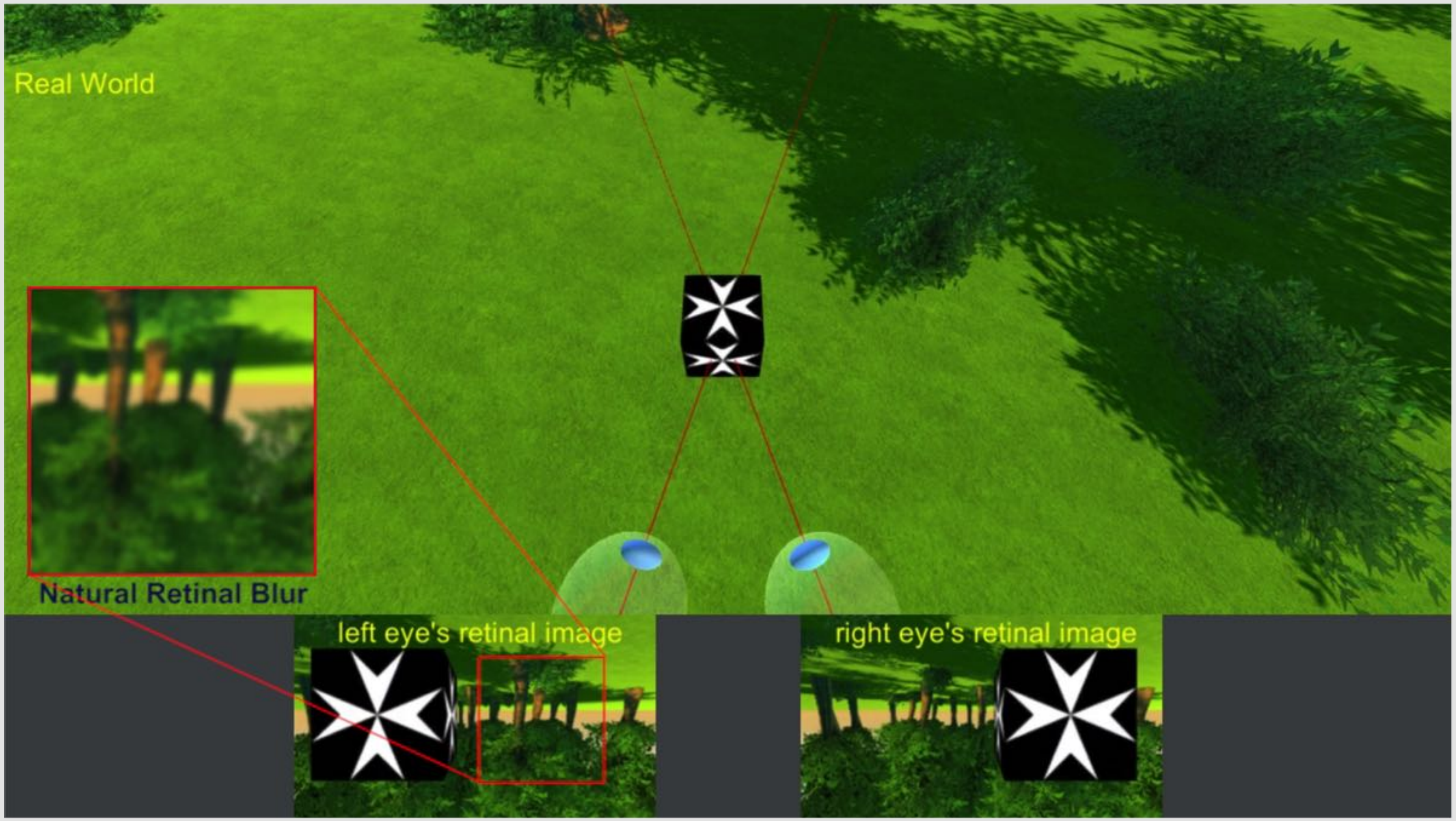
Blur in the real world



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But what about stereo displays ?

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Vergence and accommodation conflicting in near-eye displays

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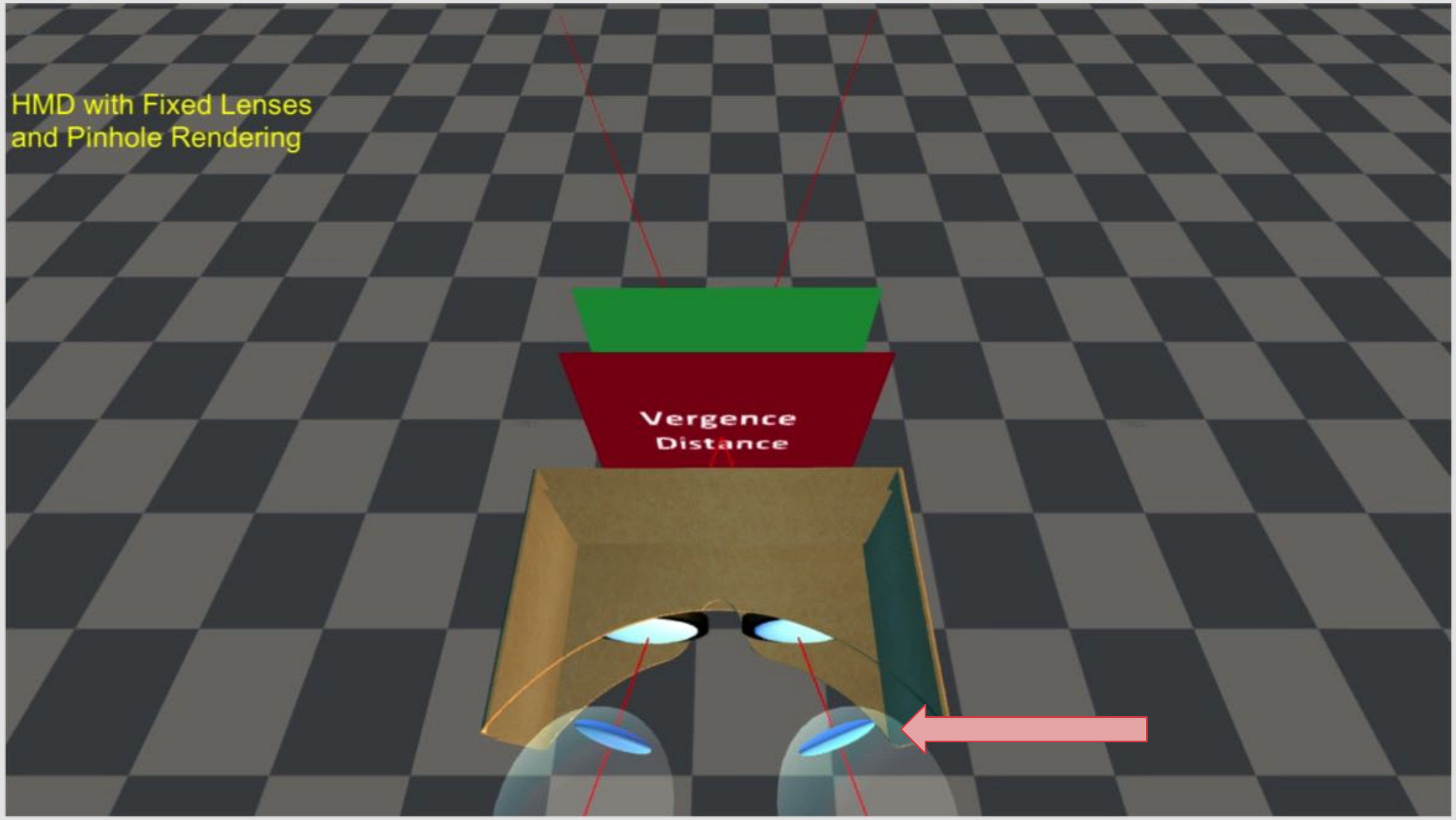

Koulieris, G. A., Bui, B., Banks, M. S., & Drettakis, G. (2017). Accommodation and comfort in head-mounted displays. *ACM Transactions on Graphics (TOG)*, *36*(4), 87.

Blur non-existent in near-eye displays

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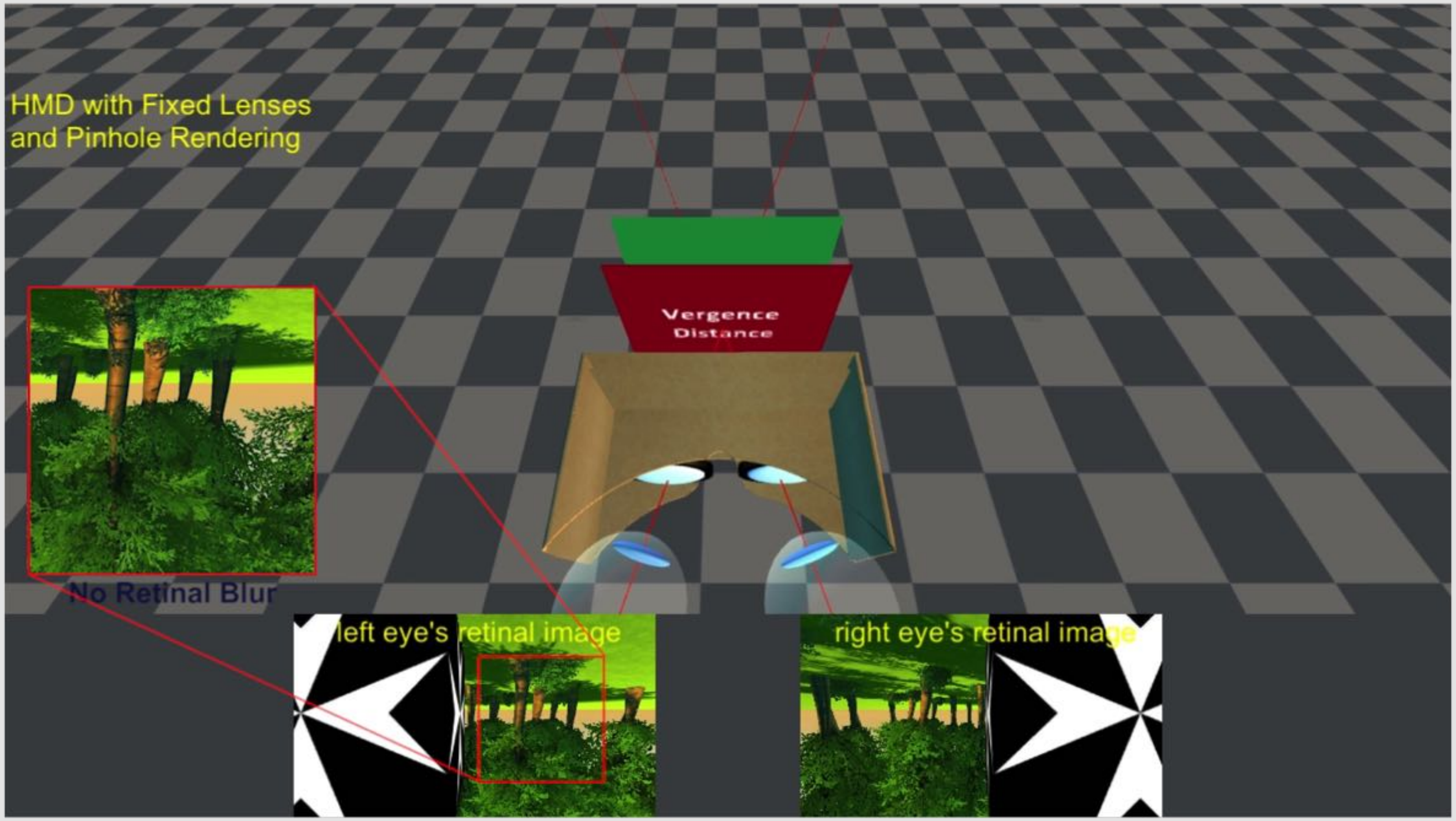

Koulieris, G. A., Bui, B., Banks, M. S., & Drettakis, G. (2017). Accommodation and comfort in head-mounted displays. *ACM Transactions on Graphics (TOG)*, *36*(4), 87.

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

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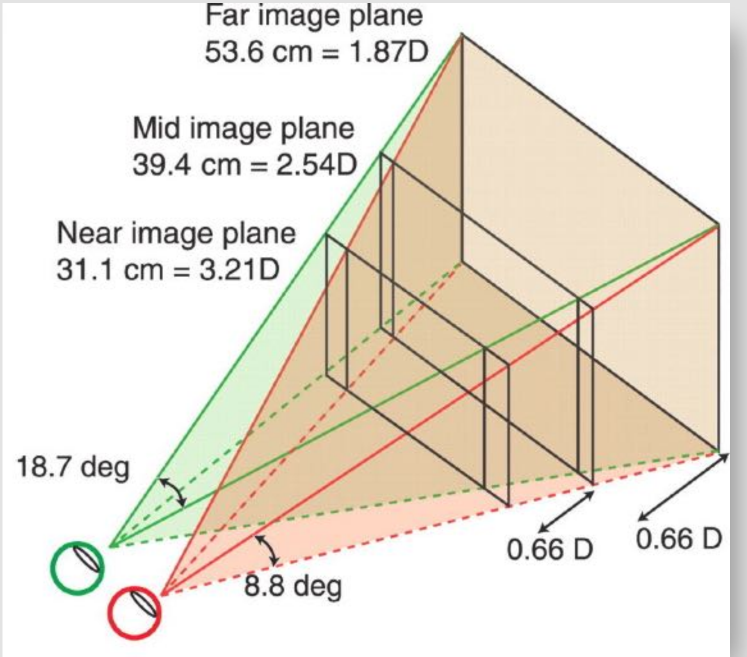
VA conflict is a major source of discomfort



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.

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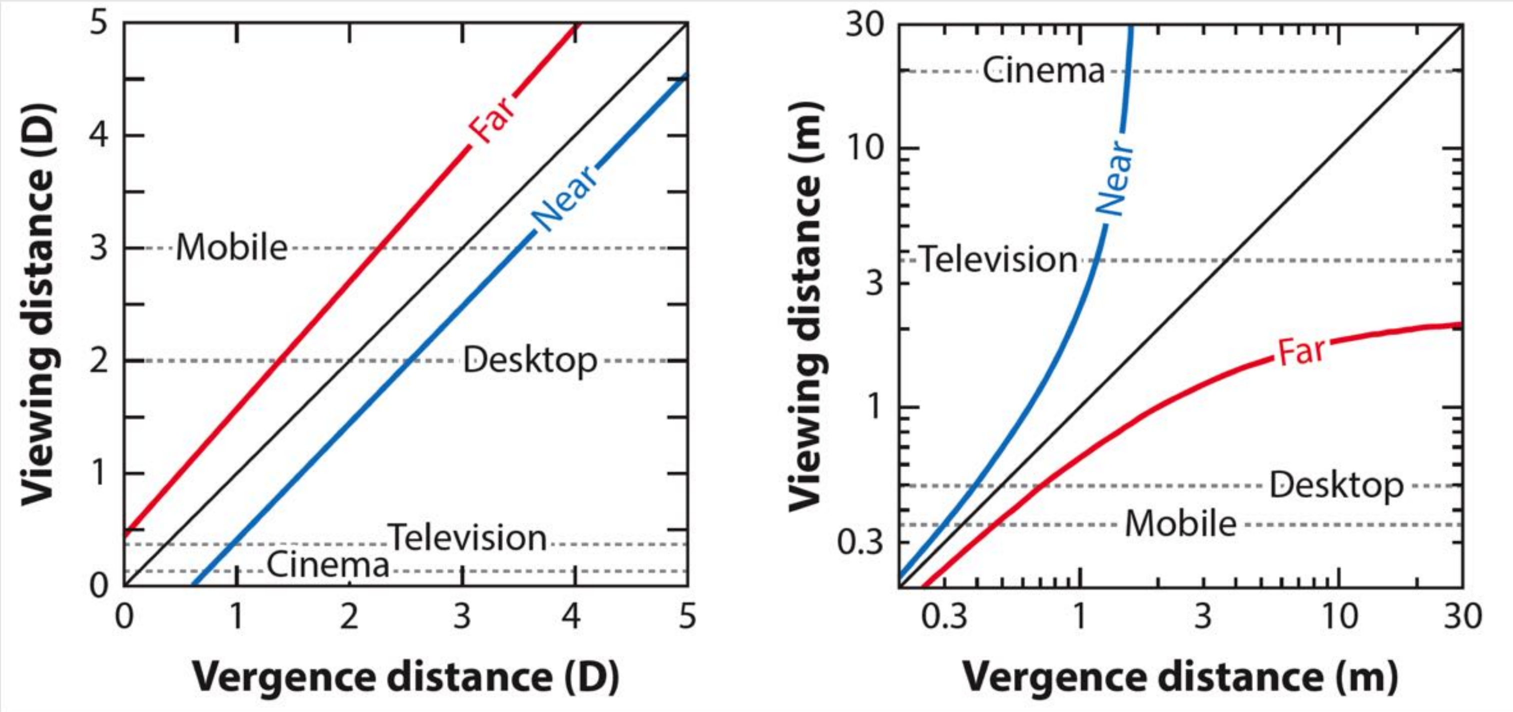
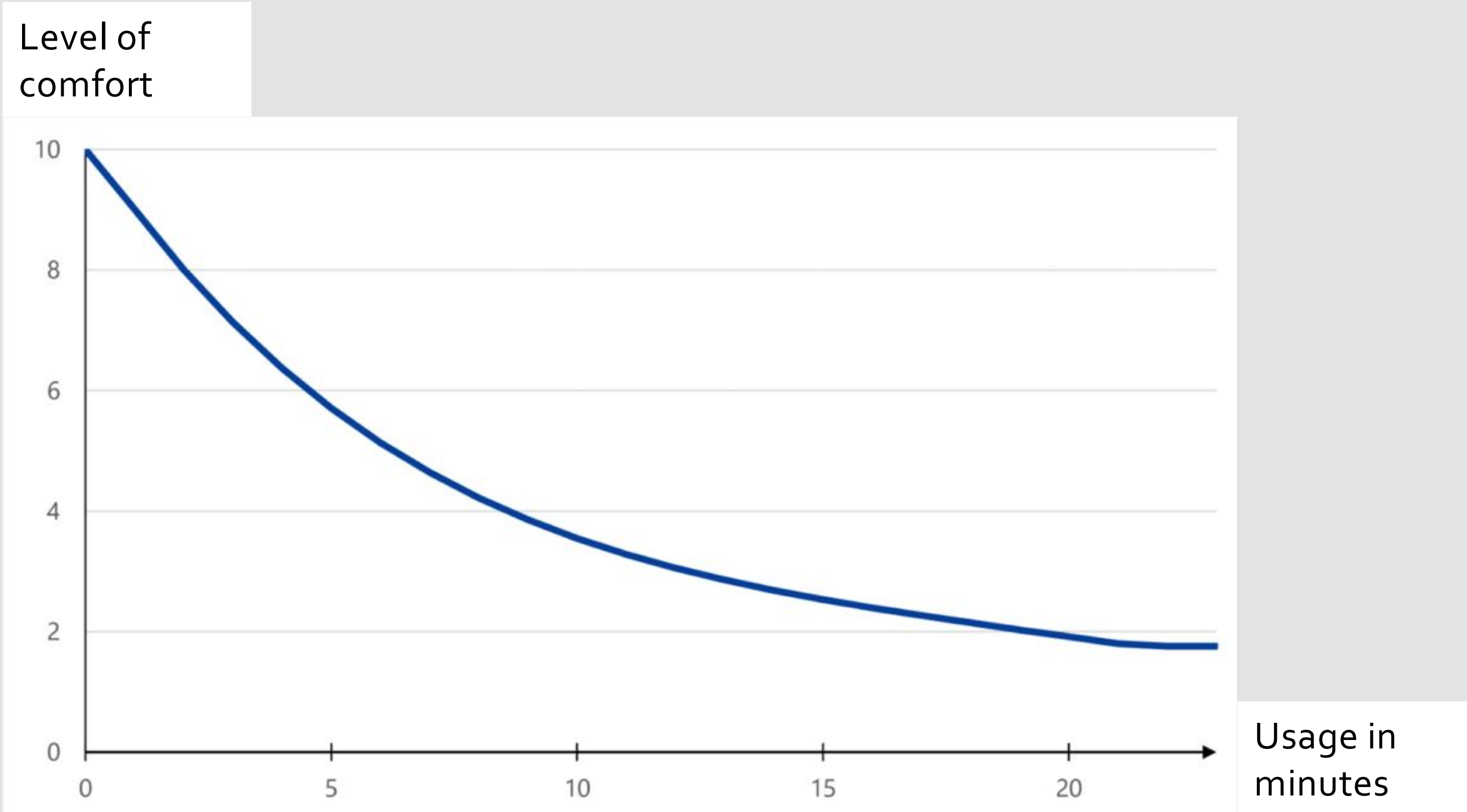
VA conflict is a major source of discomfort



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.

Comfort in VR, today



Fernandes and Feiner, 2016

VA conflict in presbyopes

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.

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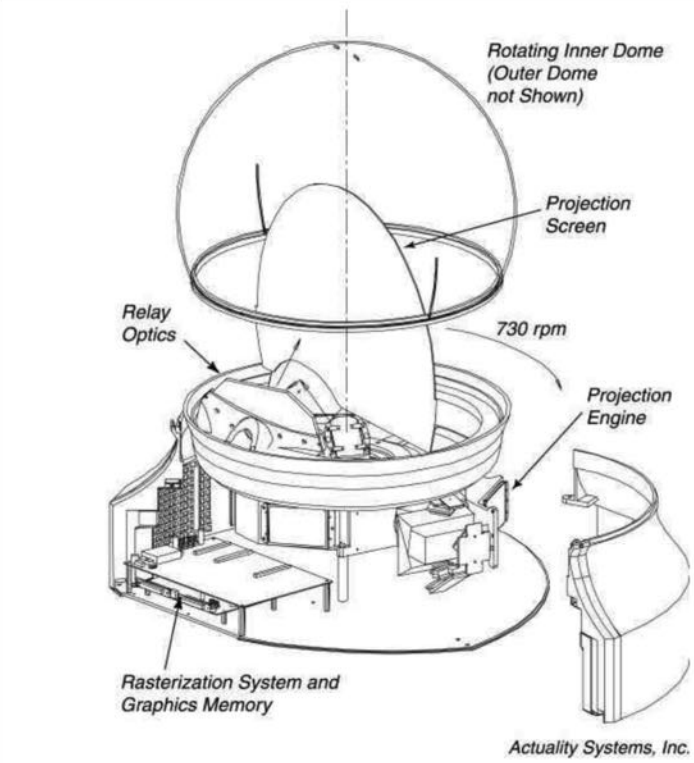
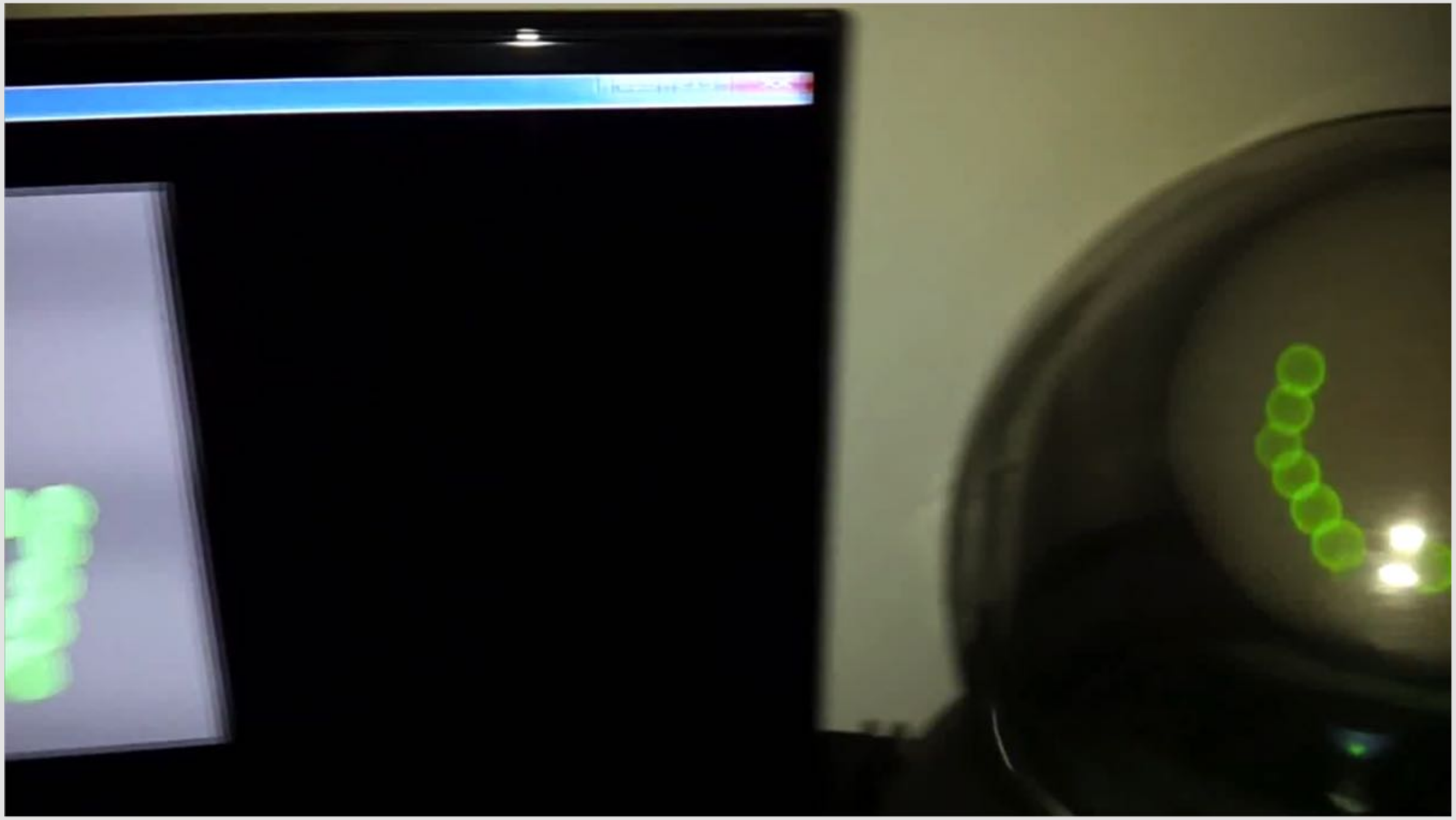
Part 2:
Multifocal displays

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.

Swept-screen volumetric displays



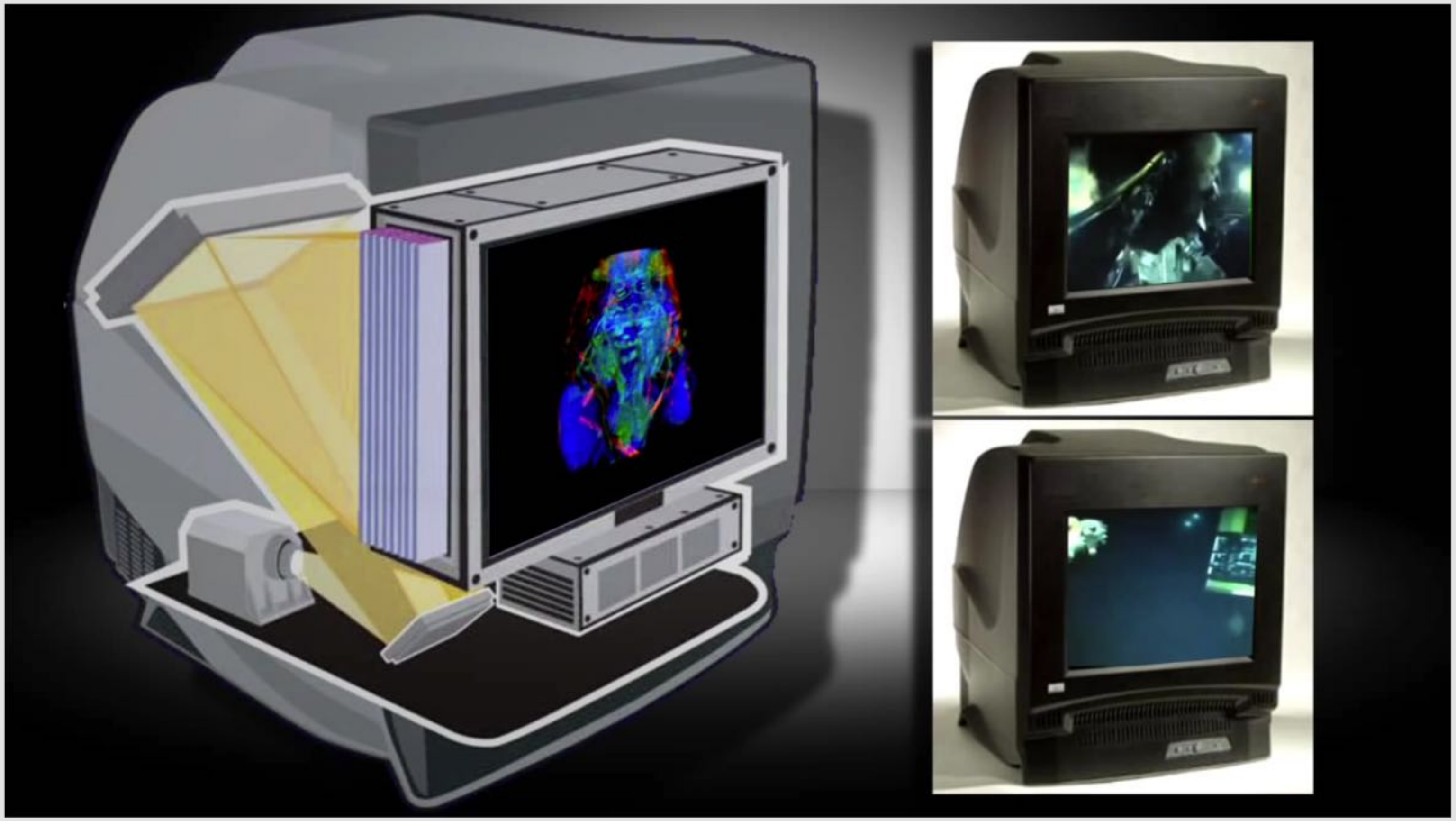
Abhijit Karnik

George-Alex Koulieris

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

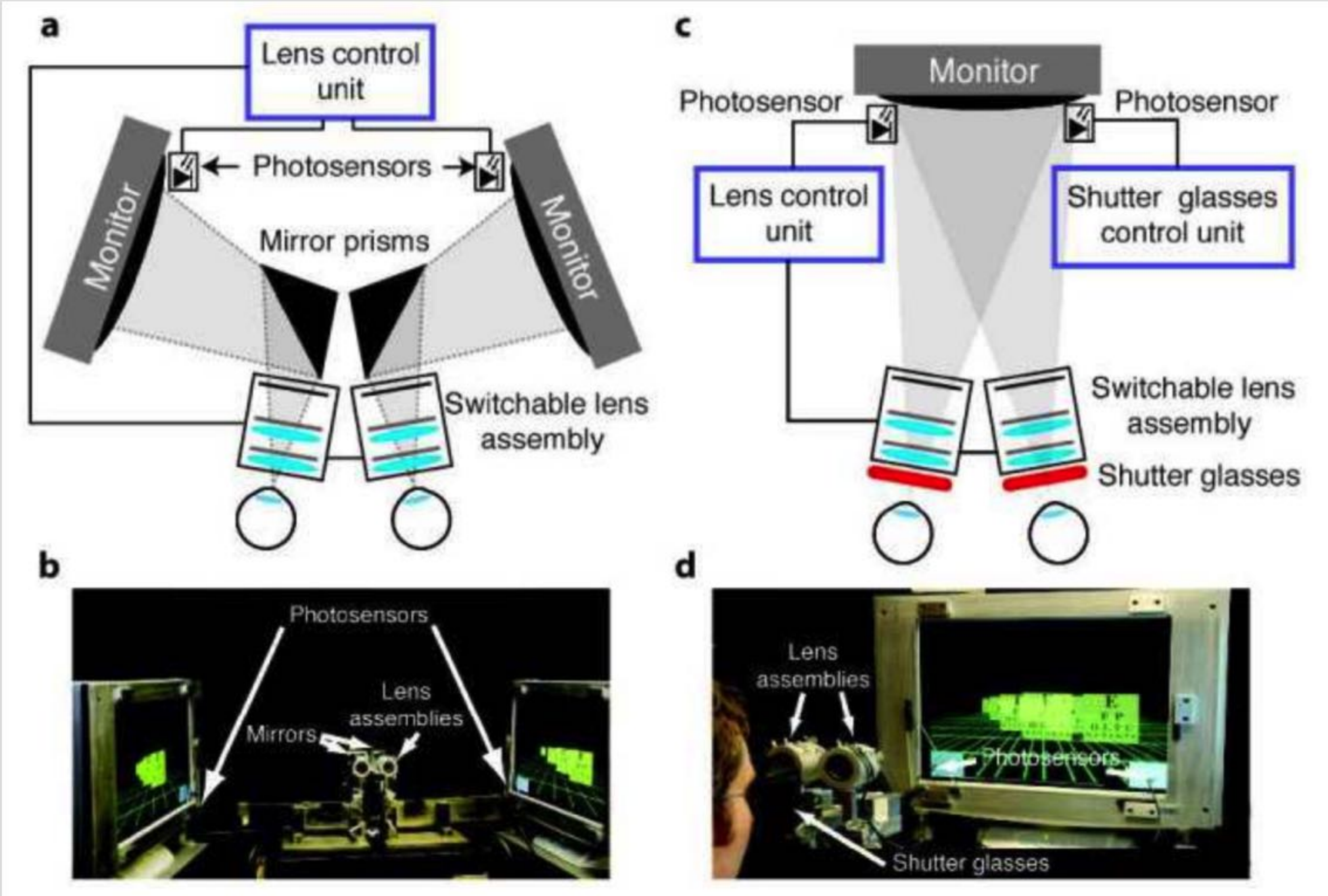
Advantages & disadvantages

- Present correct stereo, parallax and focus cues

- BUT

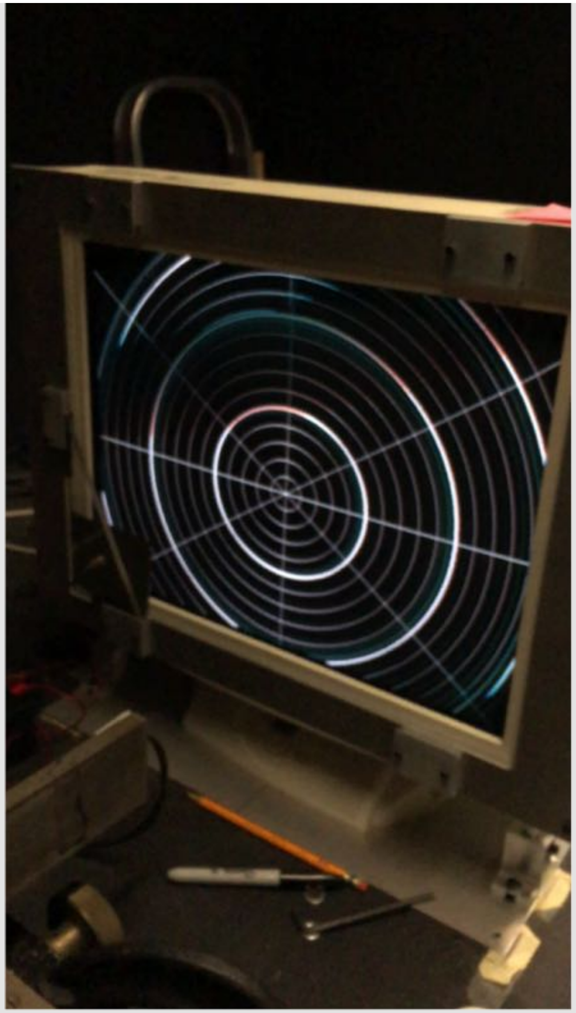
- Displayed scene confined to display volume
- Require computing and addressing a huge number of addressable voxels
- Cannot reproduce occlusions and viewpoint-dependent effects (e.g., reflections)

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.

Operation



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.

Advantages & disadvantages

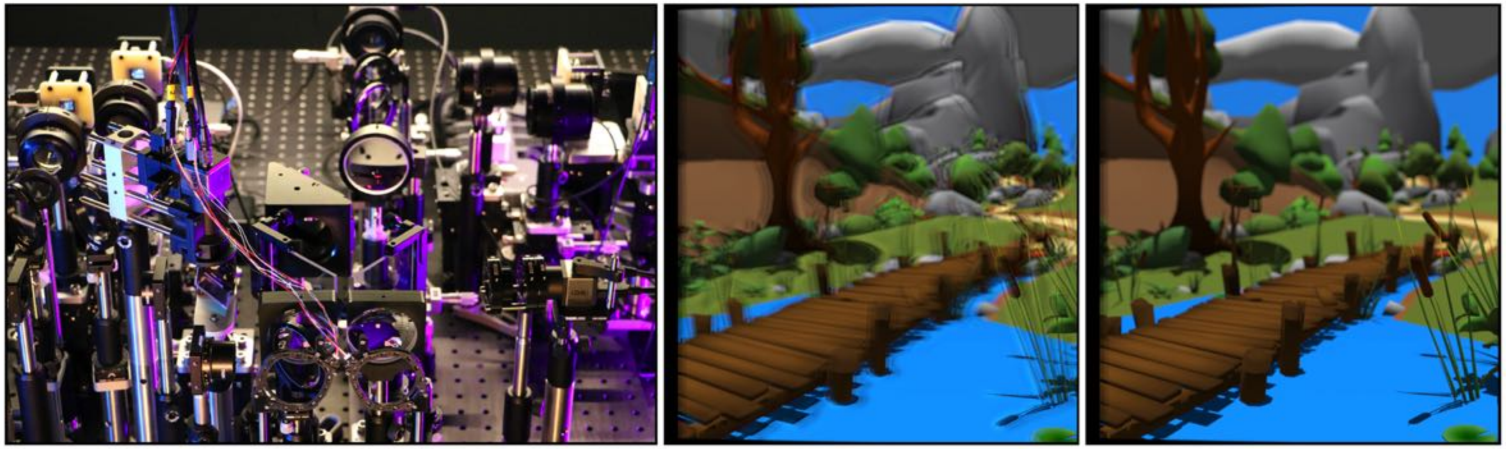
- Very high resolution
- Accommodation cues
- Comfortable

- BUT

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

Fast gaze-contingent decomposition for multifocal displays

George-Alex Koulieris



(a) Multifocal Testbed with Eye and Accommodation Tracking (b) Eye Movement without Correction (c) Eye Movement with Correction

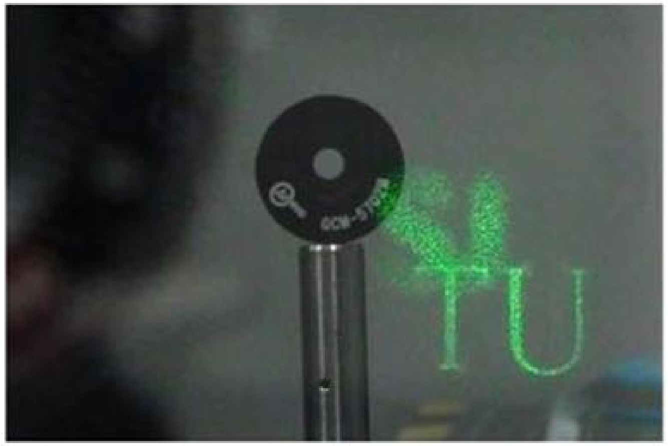
Mercier, O., Sulai, Y., Mackenzie, K., Zannoli, M., Hillis, J., Nowrouzezahrai, D., & Lanman, D. (2017). Fast gaze-contingent optimal decompositions for multifocal displays. *ACM Transactions on Graphics (TOG)*, *36*(6), 237.

Liquid lenses

Optotune

Focusing at different distances

(a)



(b)

Xuan Wang

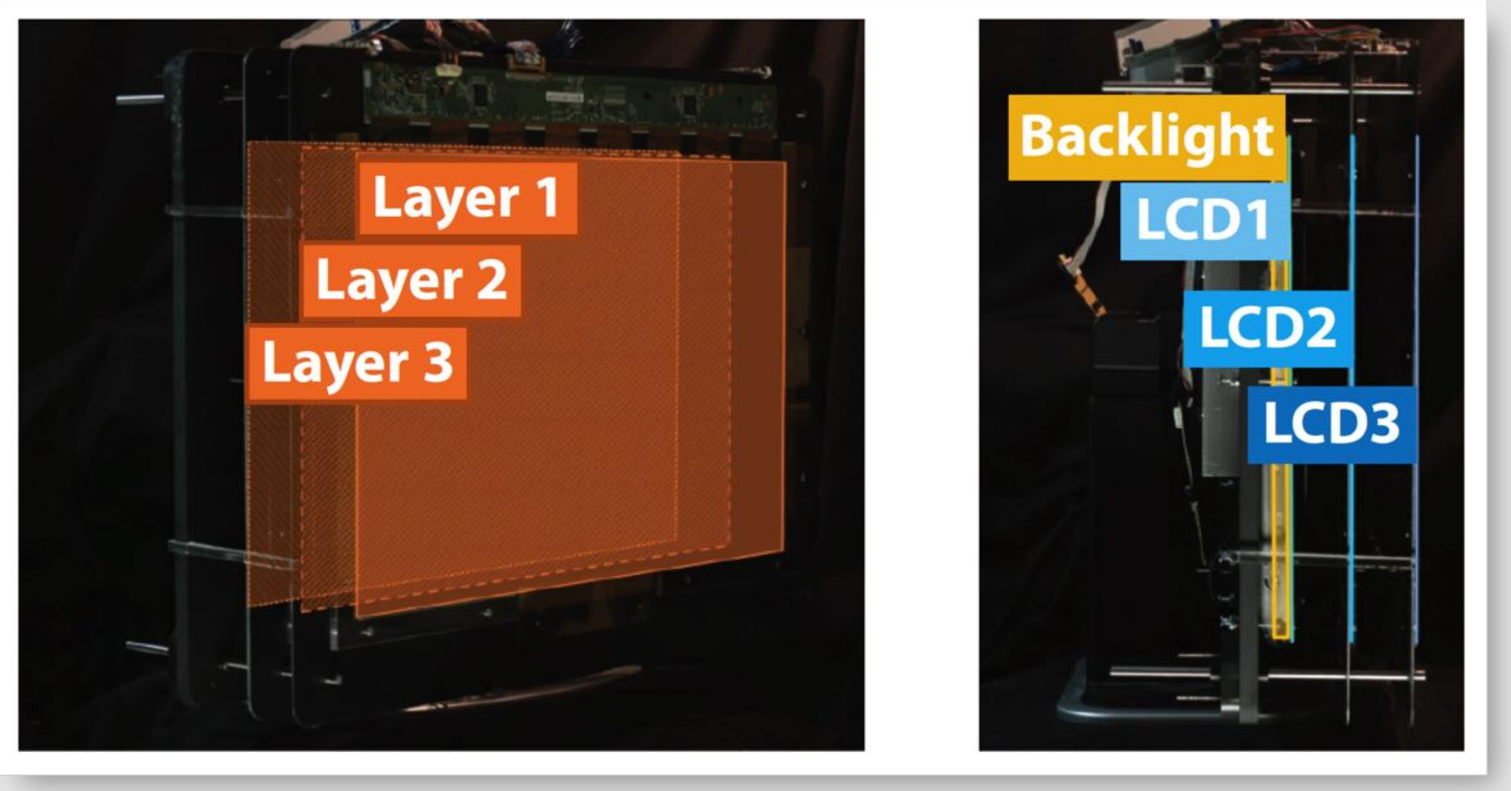
George-Alex Koulieris

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

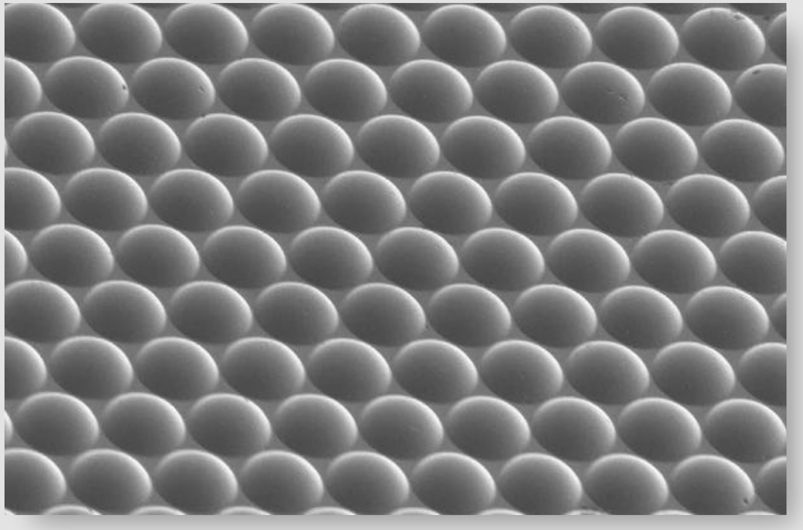


Wetzstein, G., Lanman, D., Hirsch, M., & Raskar, R. (2012). Tensor displays: compressive light field synthesis using multilayer displays with directional backlighting.

George-Alex Koulieris

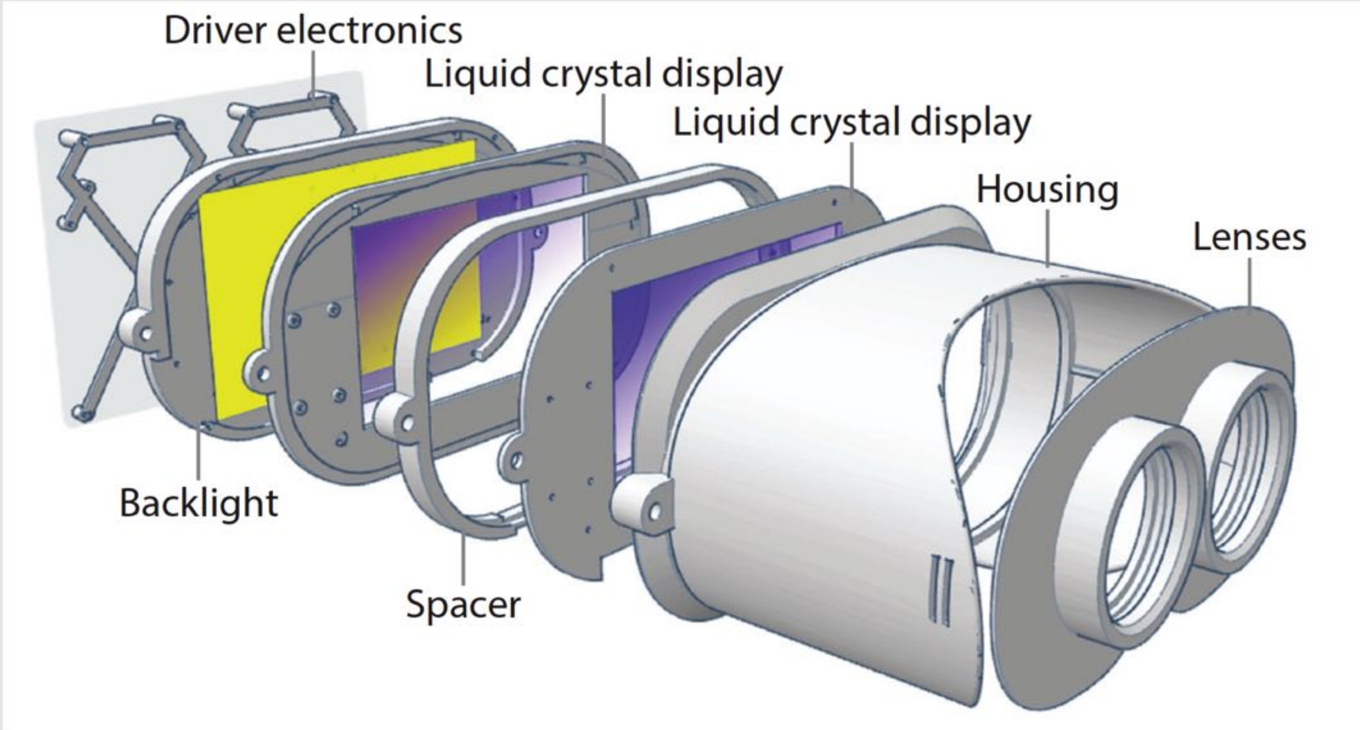
Example construction

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



Planettech International

Wearable light field displays

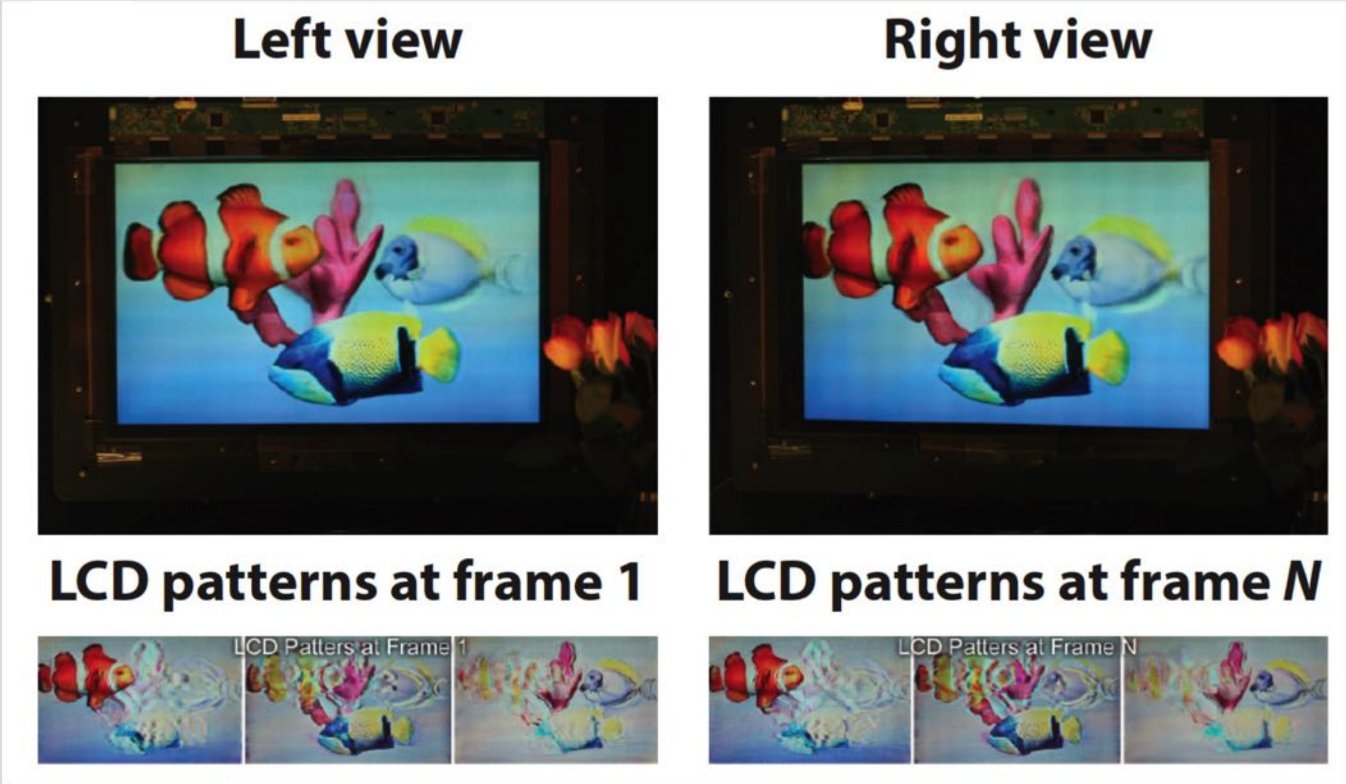


Huang et al., 2015

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.

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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Holographic near-eye displays

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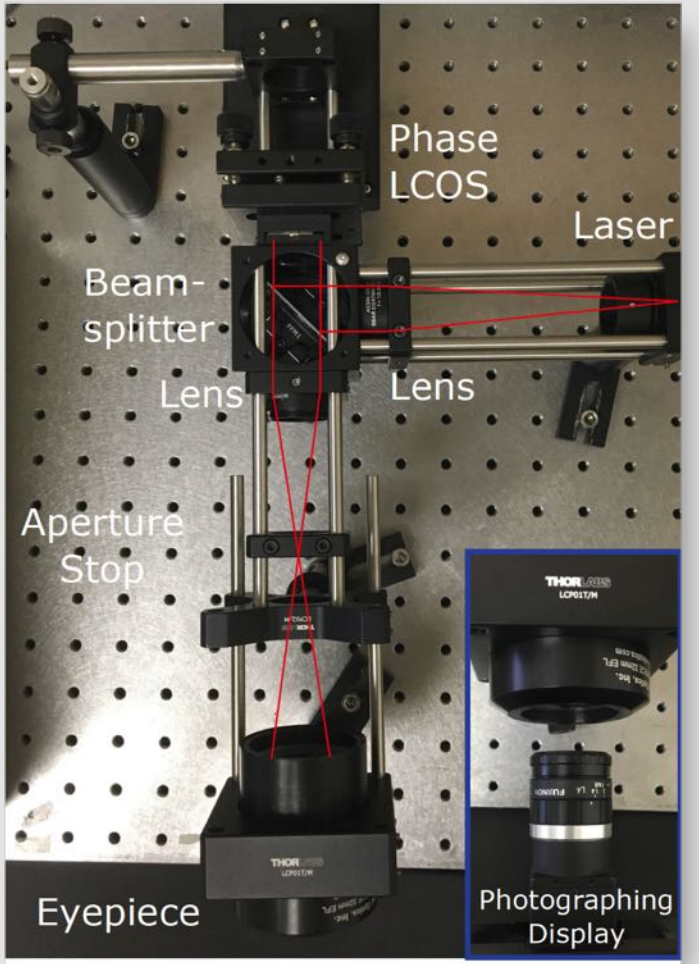
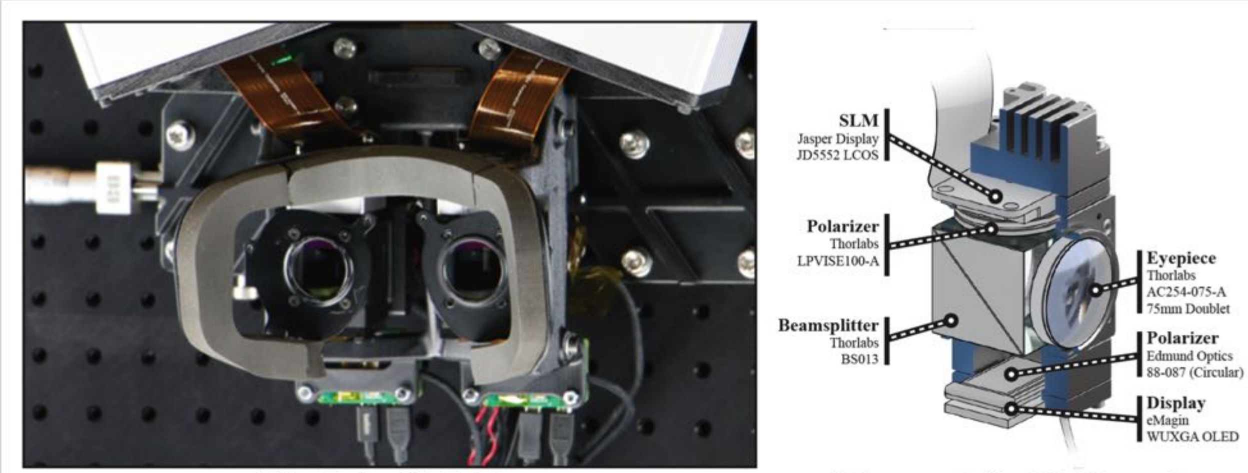
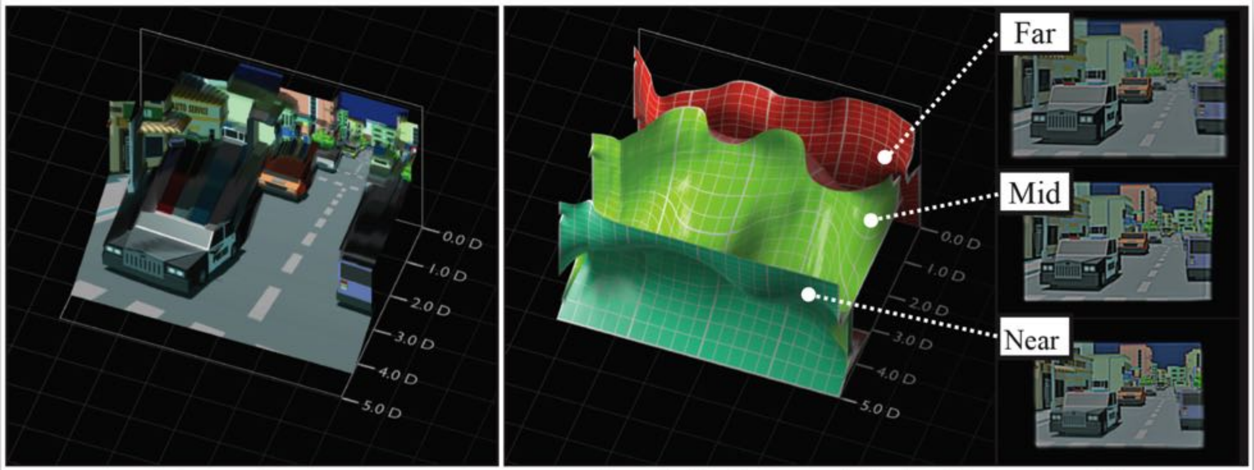


Maimone, A., Georgiou, A., & Kollin, J. S. (2017). Holographic near-eye displays for virtual and augmented reality. *ACM Transactions on Graphics (TOG)*, *36*(4), 85.

Focal surface displays



(a) Construction of the Prototype **(b)** Arrangement of the Optical Components



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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Multifocal Displays with Dense Focal Stacks

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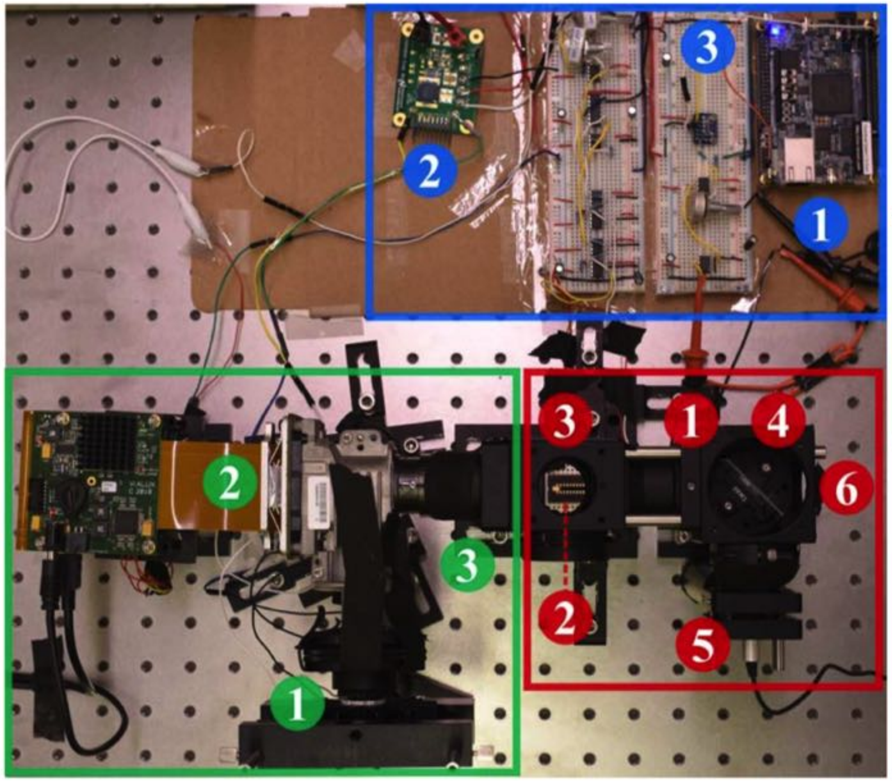
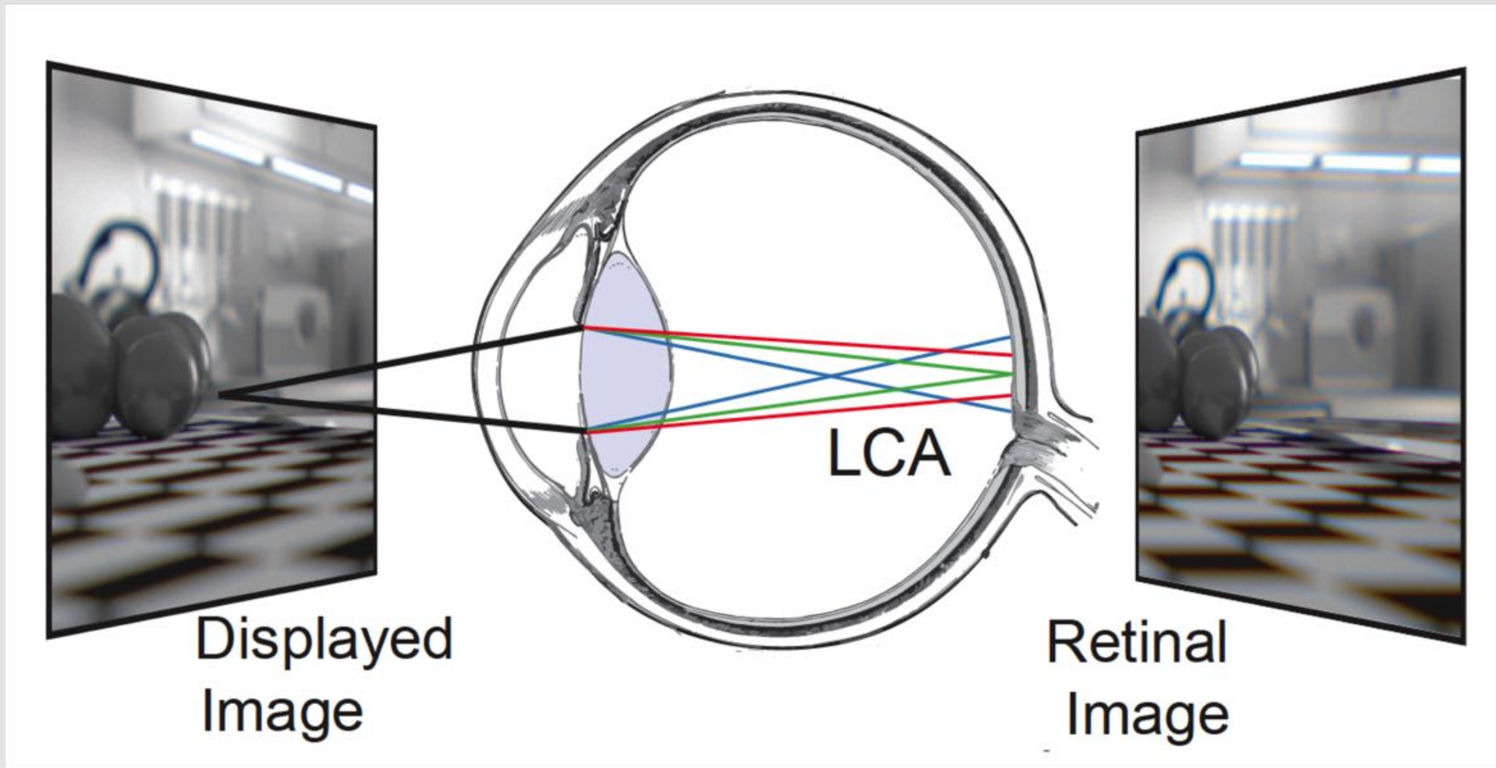


control circuit	
1	FPGA (Altera DE0-Nano-SOC)
2	LED driver (TI LM3409HV)
3	analog circuit (see Figure 6)
projector system	
1	LED (Cree XHP35A)
2	DMD (TI DLP7000)
3	projection optics (Vialux)
focal-length tracking module	
1	focus-tunable lens (Optotune EL-10-30)
2	position sensing detector (OSI Optoelectronics SL15)
3,4	shortpass dichroic mirror (Edmund Optics 69-220)
5	collimated infrared laser (Thorlabs CPS980S)
6	eye piece

Chang, J. H. R., Kumar, B. V. K., & Sankaranarayanan, A. C. (2018). Towards Multifocal Displays with Dense Focal Stacks. In *SIGGRAPH Asia 2018 Technical Papers*

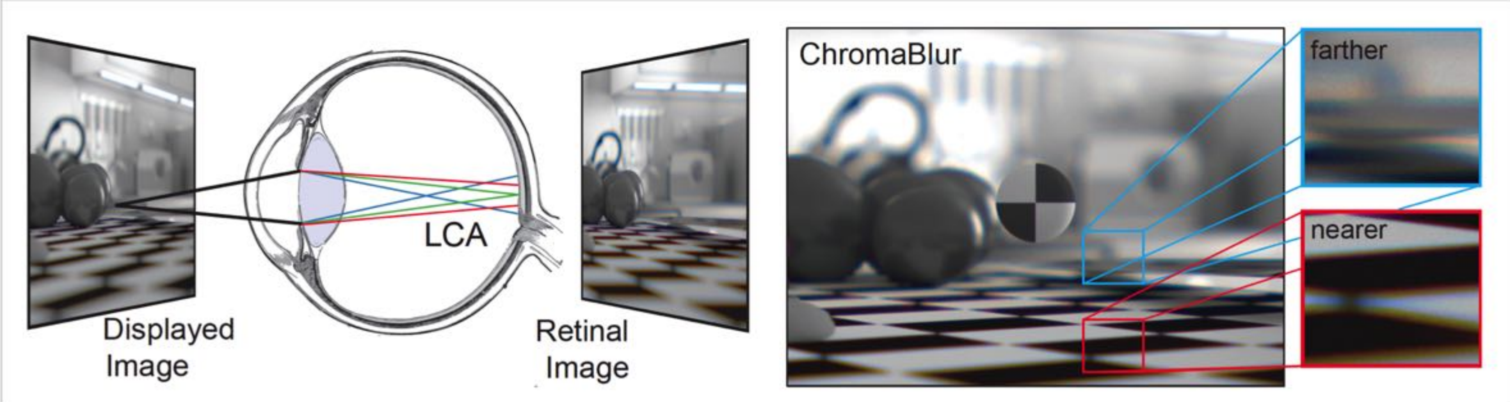
Rendering chromatic aberration

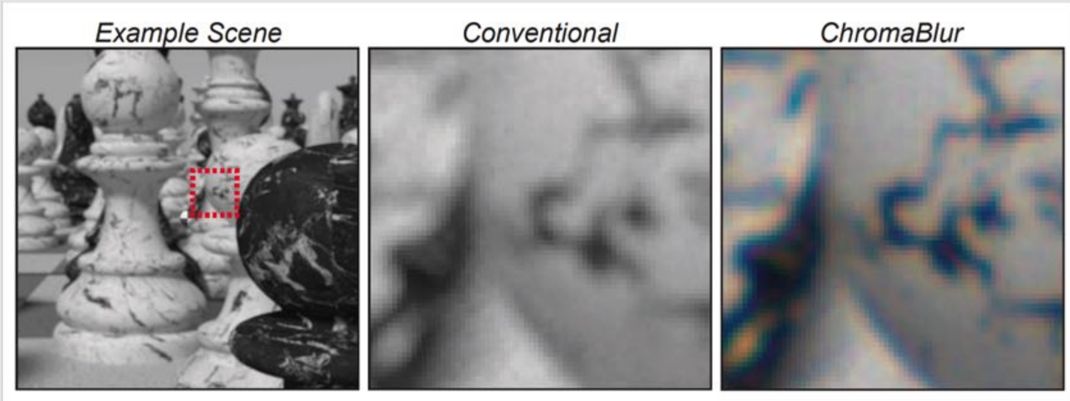


adapted from Cholewiak et al., 2017

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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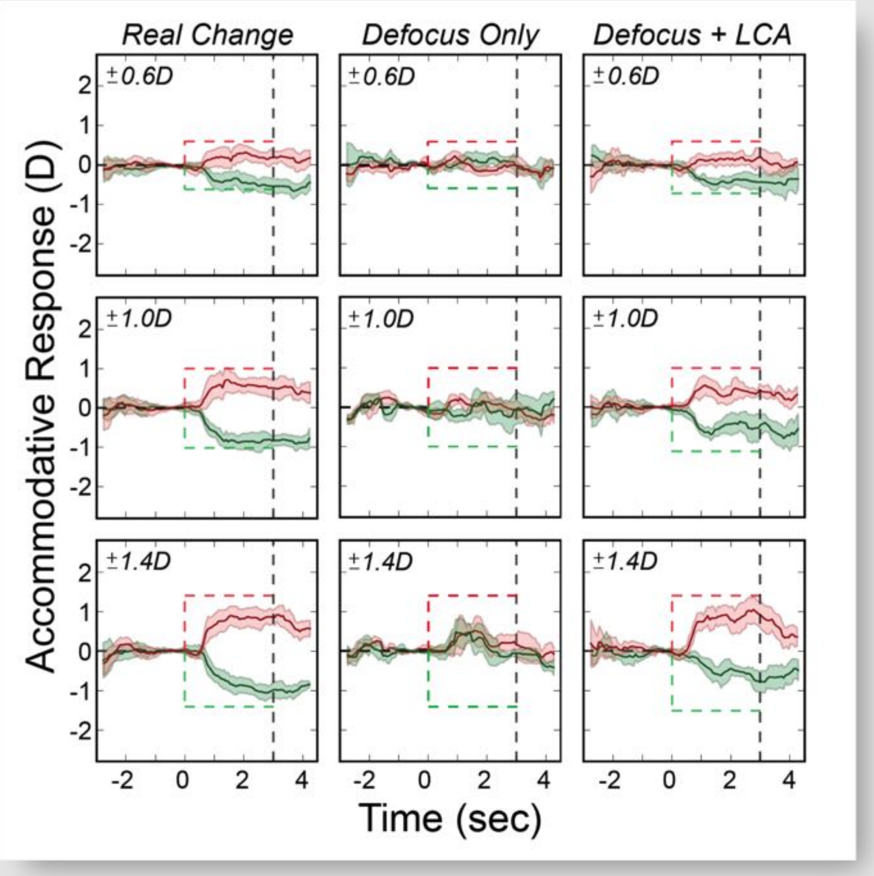
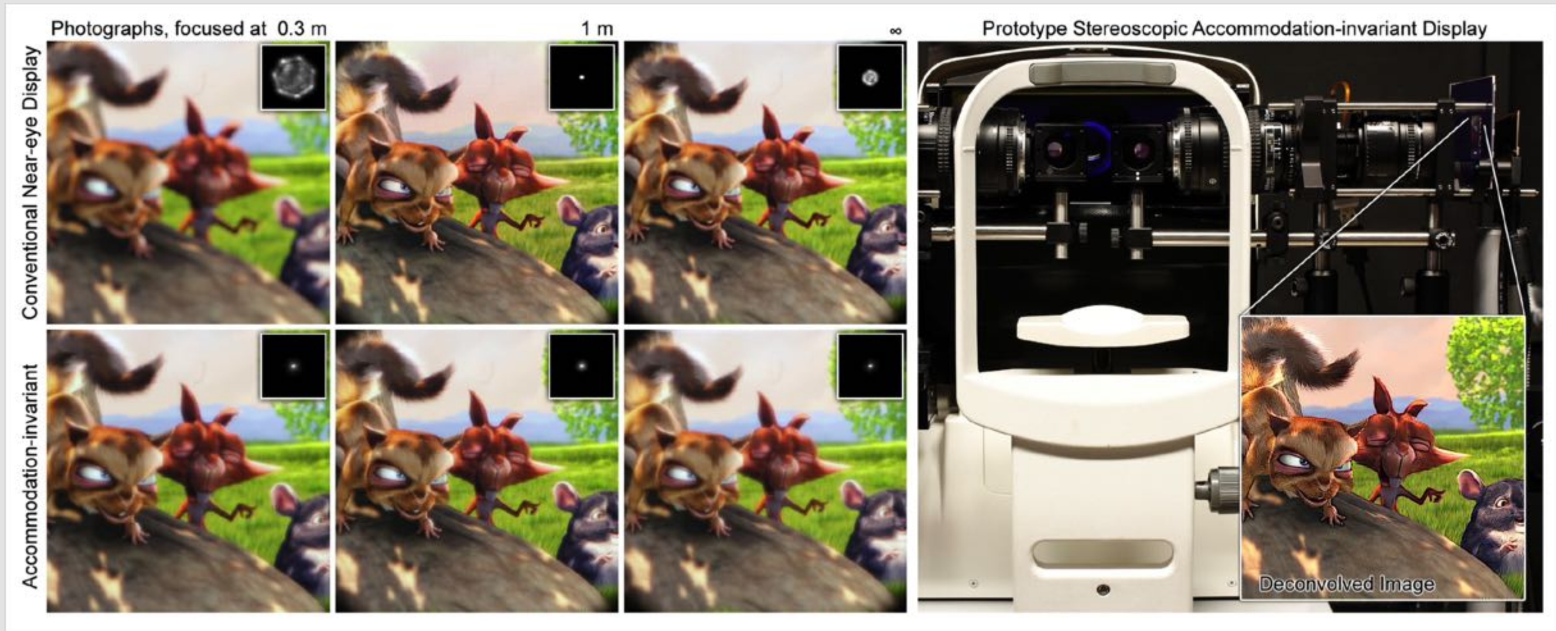
Rendering chromatic aberration



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.

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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DeepFocus: Learned Image Synthesis for Computational Displays

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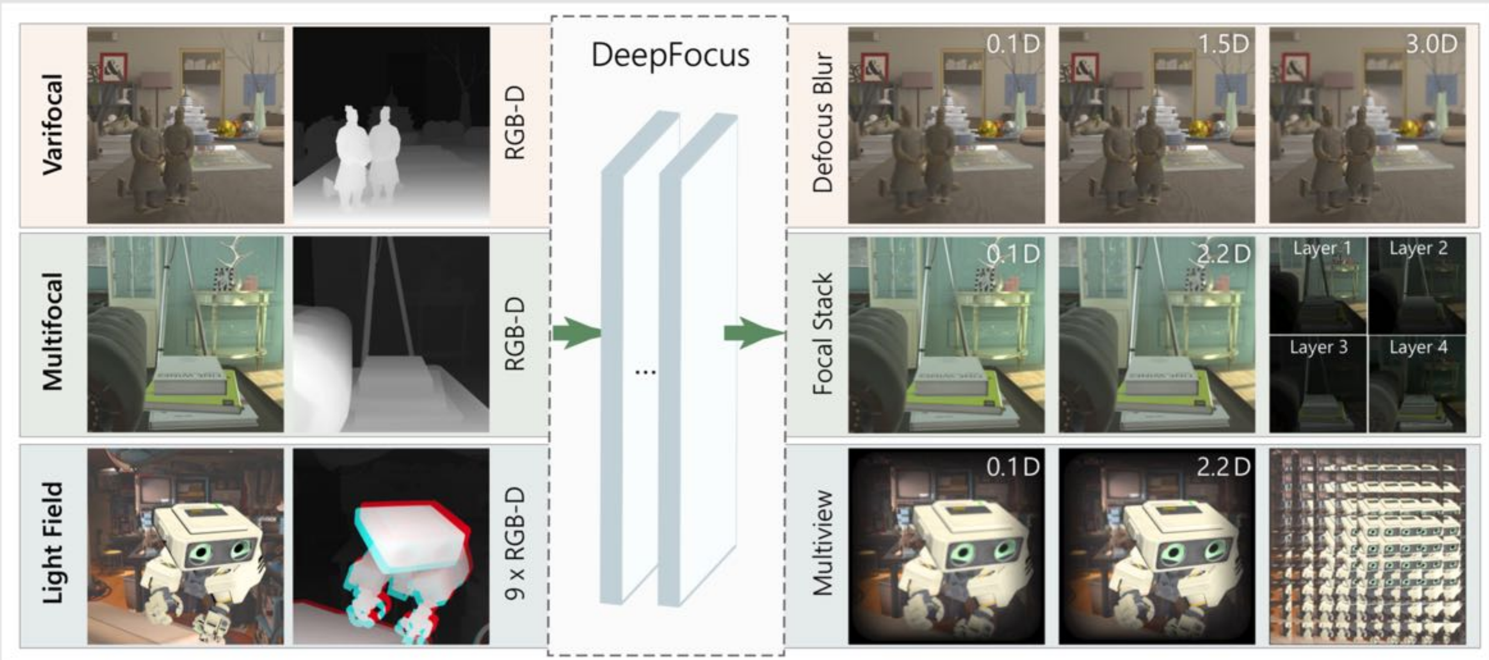

Xiao, L., Kaplanyan, A., Fix, A., Chapman, M., & Lanman, D. (2018, December). DeepFocus: learned image synthesis for computational displays. In *SIGGRAPH Asia 2018 Technical Papers* (p. 200). ACM.

Software-only methods

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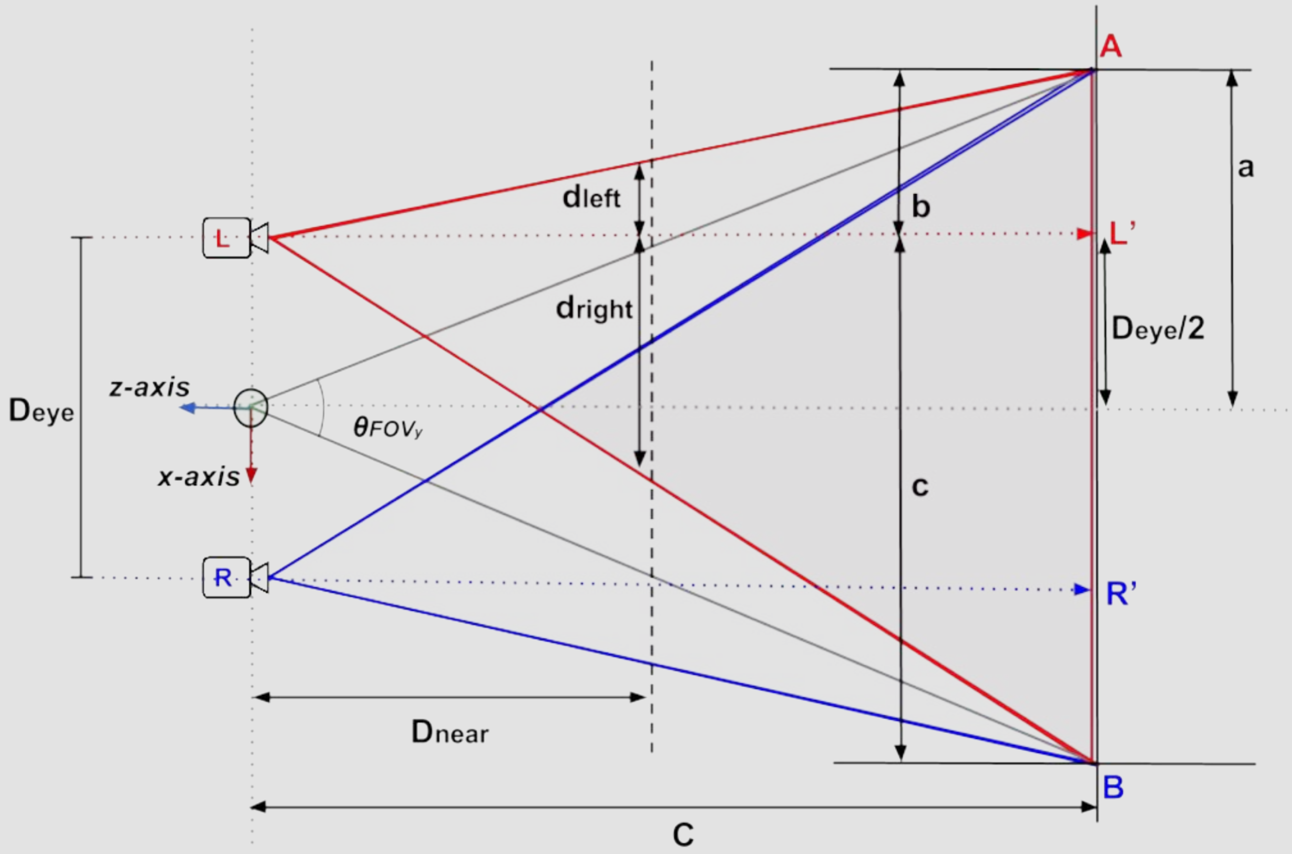
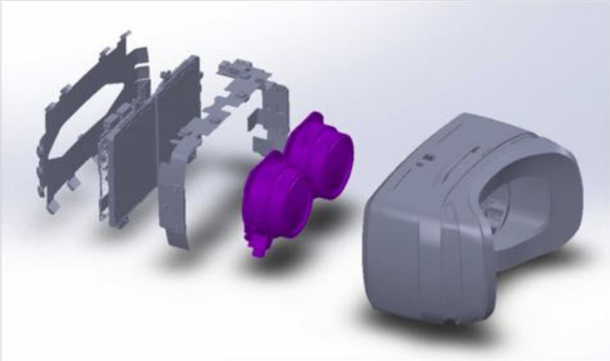


Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2016, March). Gaze prediction using machine learning for dynamic stereo manipulation in games. In *Virtual Reality (VR), 2016 IEEE* (pp. 113-120). IEEE.

Verifocal by Lemnis Technologies



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Oculus *half-dome*

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Summary

- Addressing VA conflict fundamental to eliminate discomfort in HMDs
- Necessary for widespread adoption of near-eyes displays

Thank you
Questions?

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https://vrdisplays.github.io/sigasia2018/

Schedule

Start	Topic	Speaker
14:15	Introduction	George Alex Koulieris
14:30	Multi-focal displays	George Alex Koulieris
15:05	Near-eye varifocal AR	Kaan Akşit
15:50	Coffee break	
16:00	HDR-enabled displays	Rafał Mantiuk
16:45	Motion-aware displays	Christian Richardt
17:30	Demos & Summary	All presenters