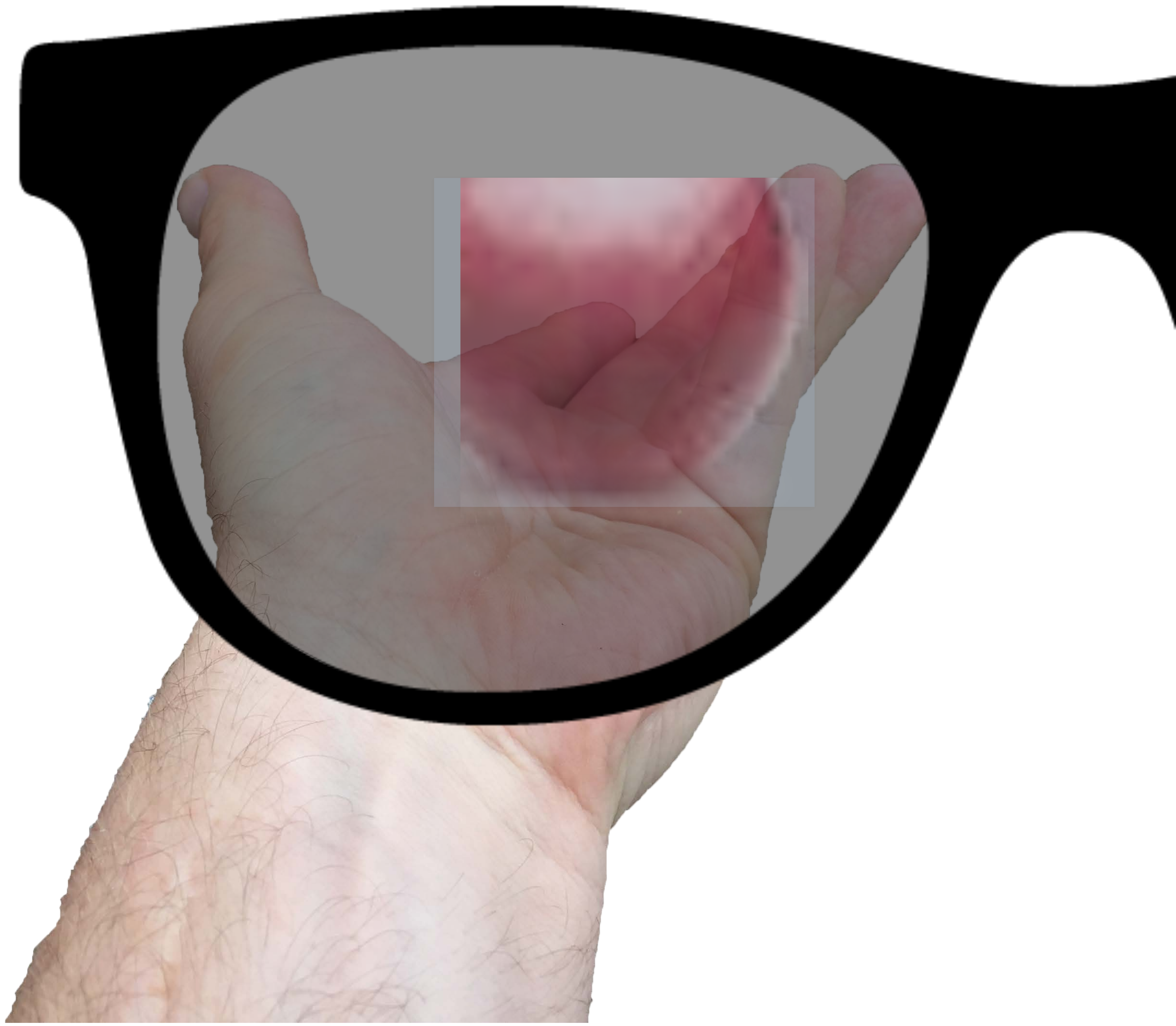
ARIVE

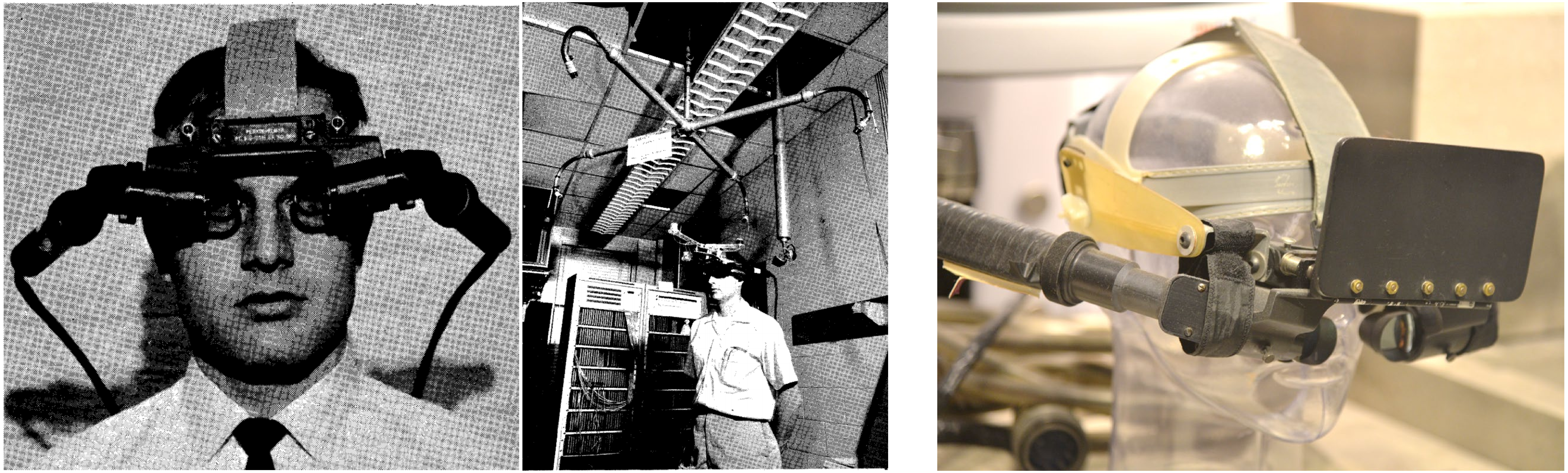


Towards Indistinguishable Augmented Reality in Optical See-Through Head-Mounted Displays

tobias langlotz, yuta itoh, jonathan sutton, alexander plopski

The University of Auckland
UNSW
University of Canterbury
Monash University
University of Otago
The University of Queensland
Victoria University Wellington
University of South Australia

Motivation



Sutherland: “A head-mounted three dimensional display” [147]

Microsoft Hololens

Magic Leap

tobias langlotz, yuta itoh, jonathan sutton, alexander plopski

Overview:

- Reviewed and discussed ~170 papers in the field of hardware (e.g. optics) and software (e.g. rendering)
- Focus on academic papers not patents or speculation on non disclosed implementation details
- Target unique issues to OST HMDs
- Goal: Visually indistinguishable AR overlays

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- Target unique issues to OST HMDs
- Goal: Visually indistinguishable AR overlays on OST HMDs

Indistinguishable Augmented Reality on Optical See-Through Head-Mounted Displays

Spatial Realism:	Temporal Realism:	Visual Realism:
• Spatial calibration • Distorsion correction	• System Latency • Display latency and flickr	• Colour • Dynamic range • Accomodation capability • Occlusion capability • Wide field of view • Resolution

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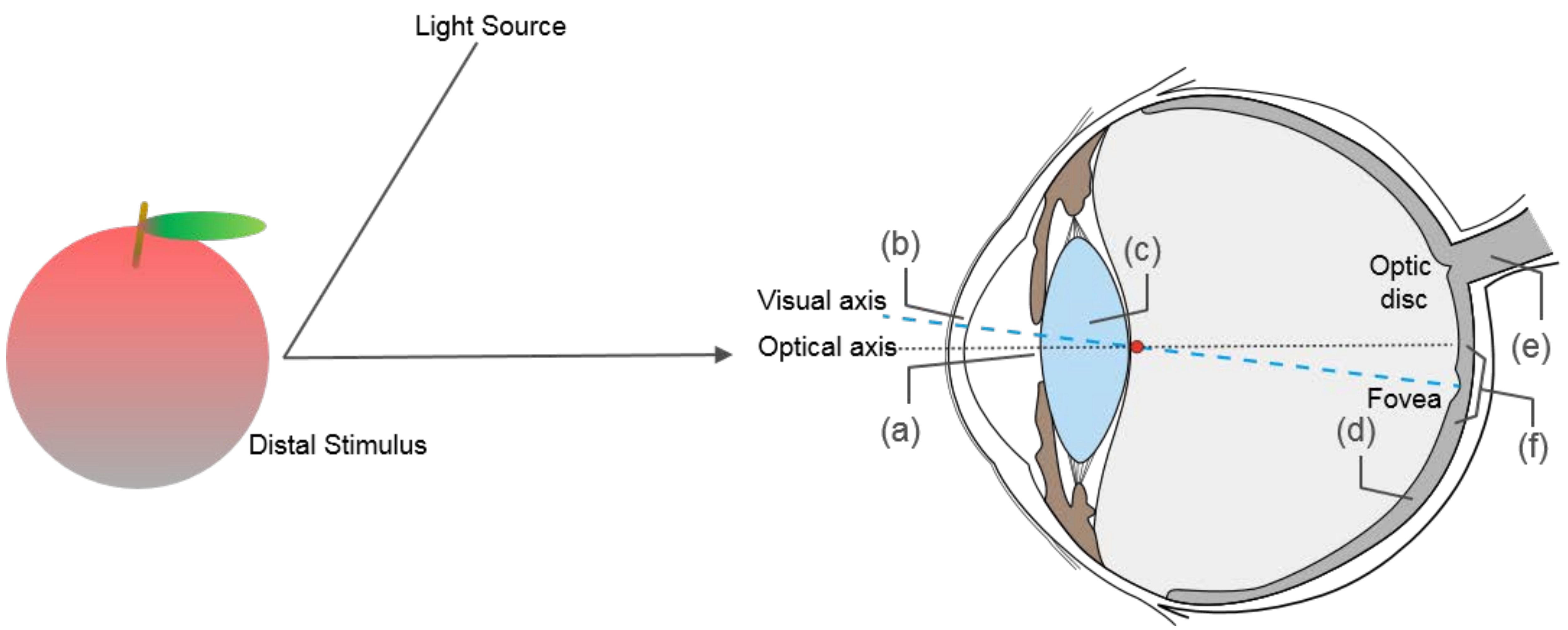
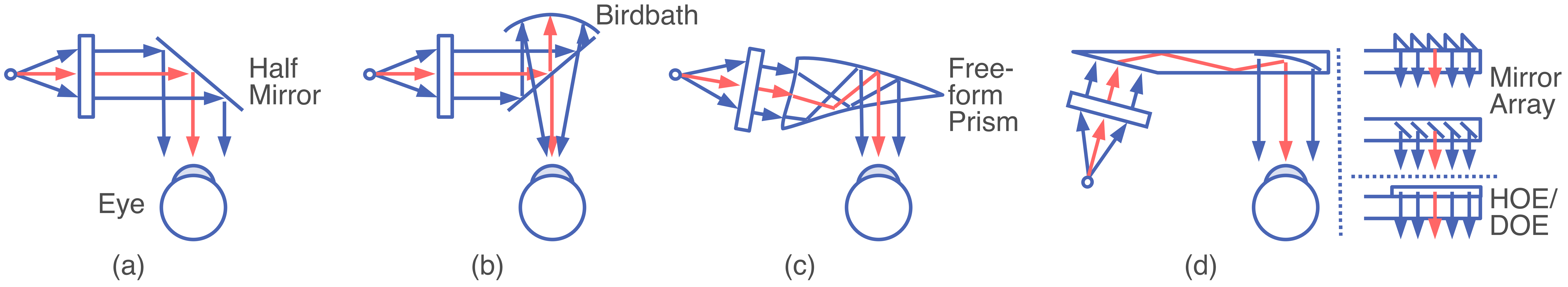
- No time today but discussed extensively in our paper:
  - Human visual system - Physiology and Perception

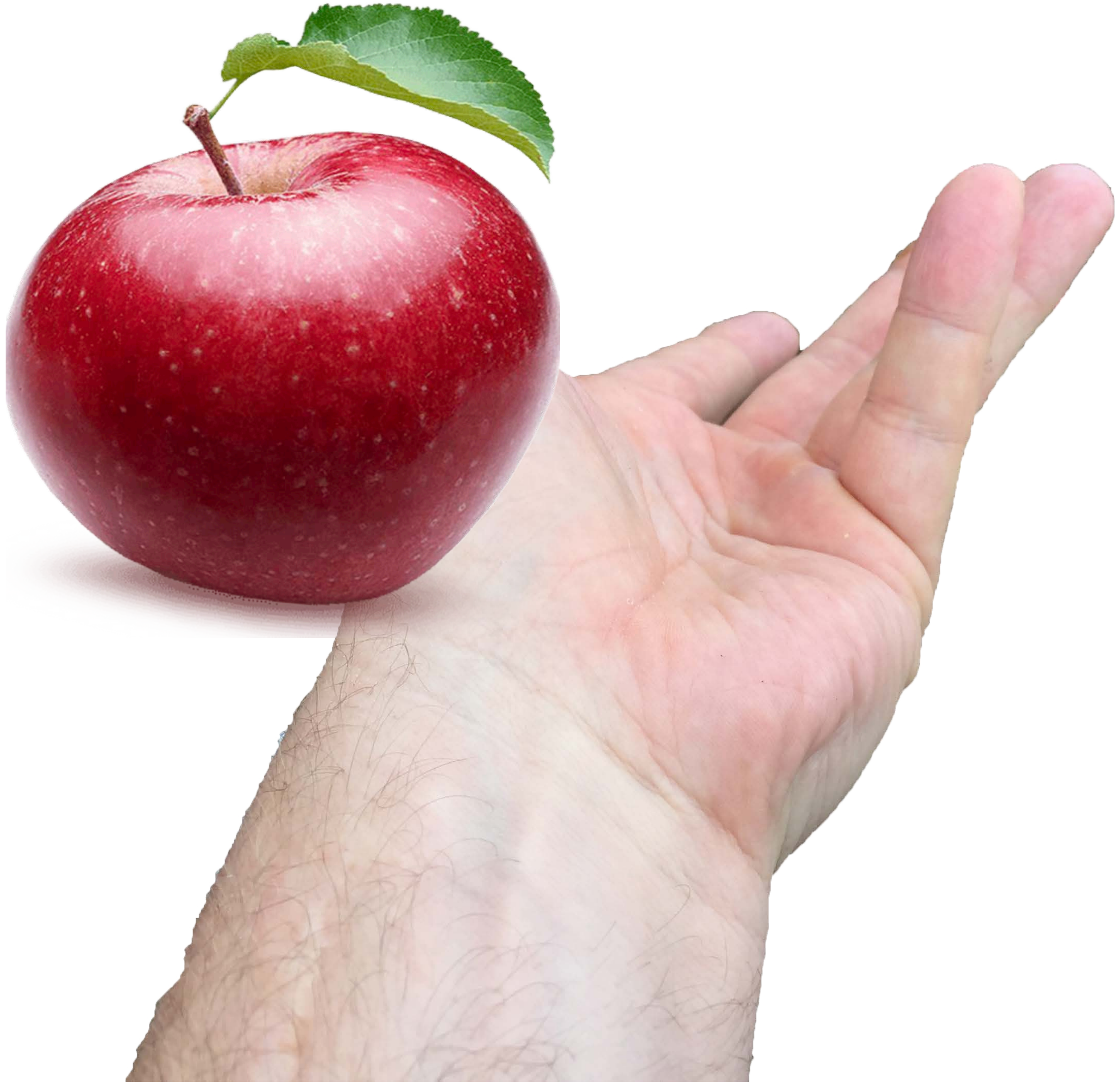


  - Basic optical designs of OST

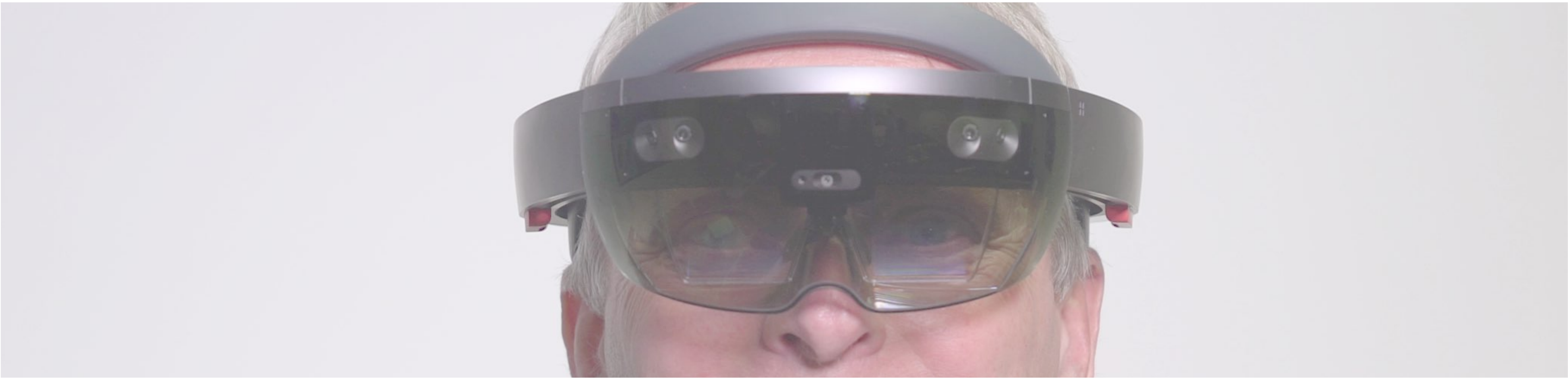


Spatial Realism

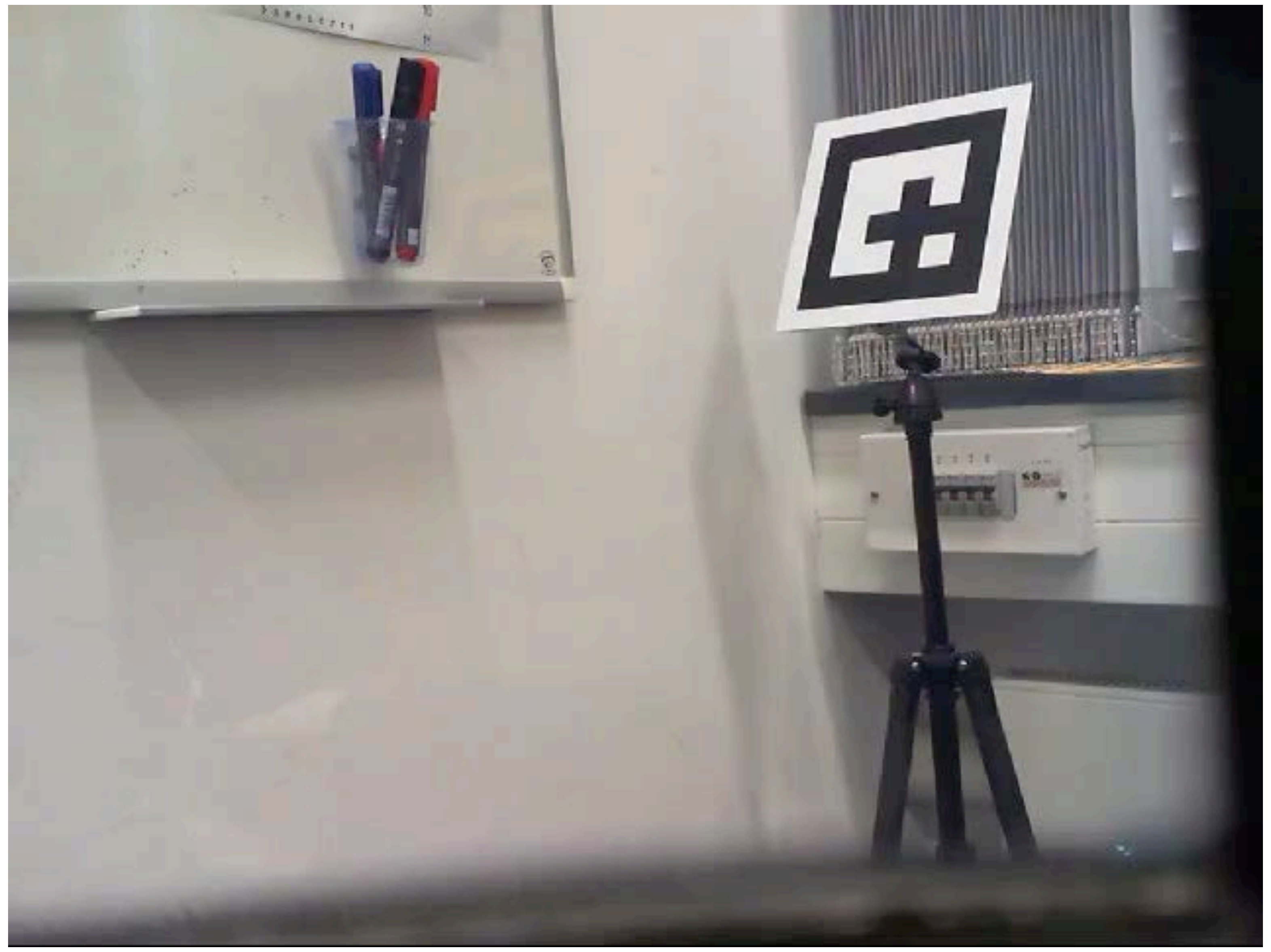
Vs.

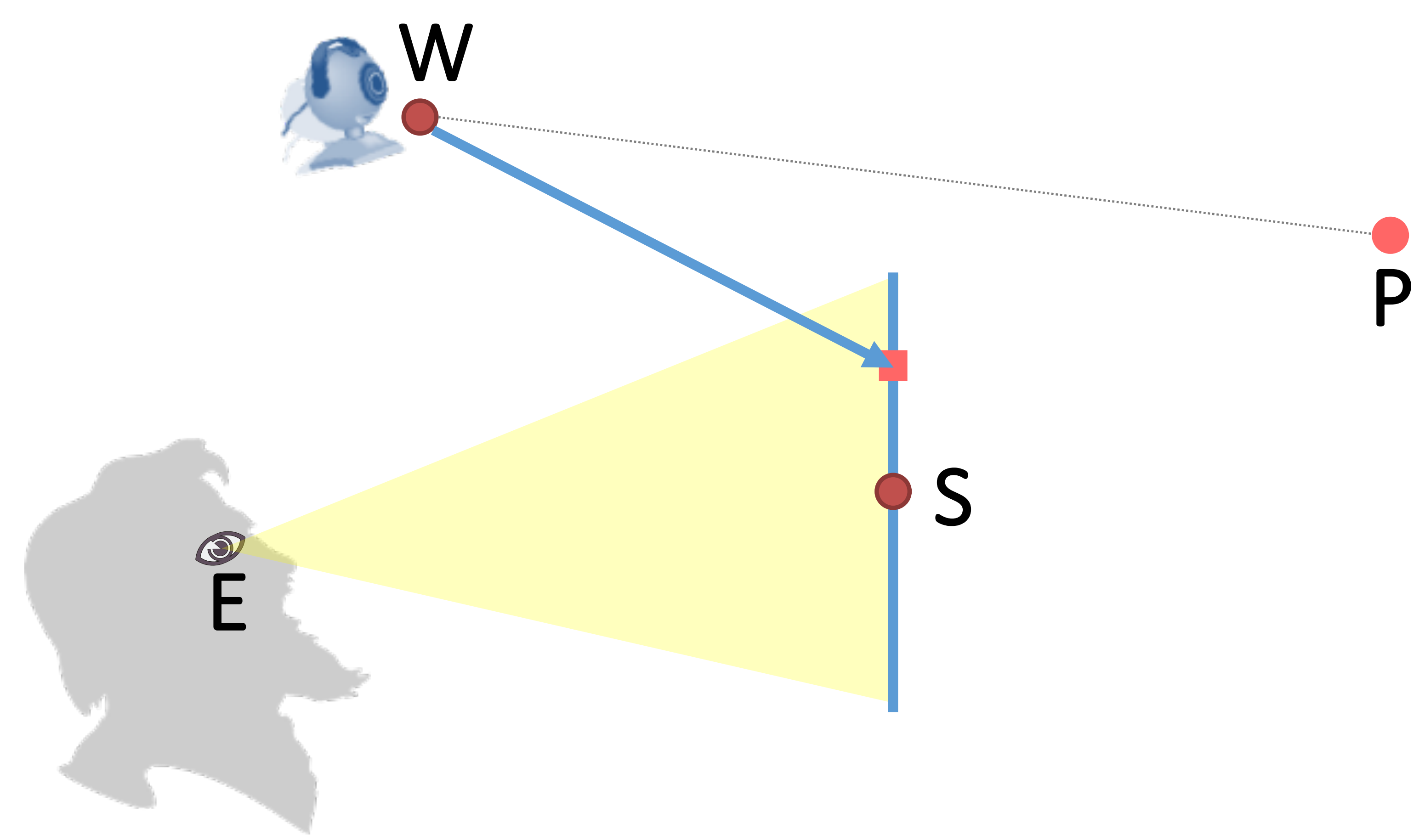


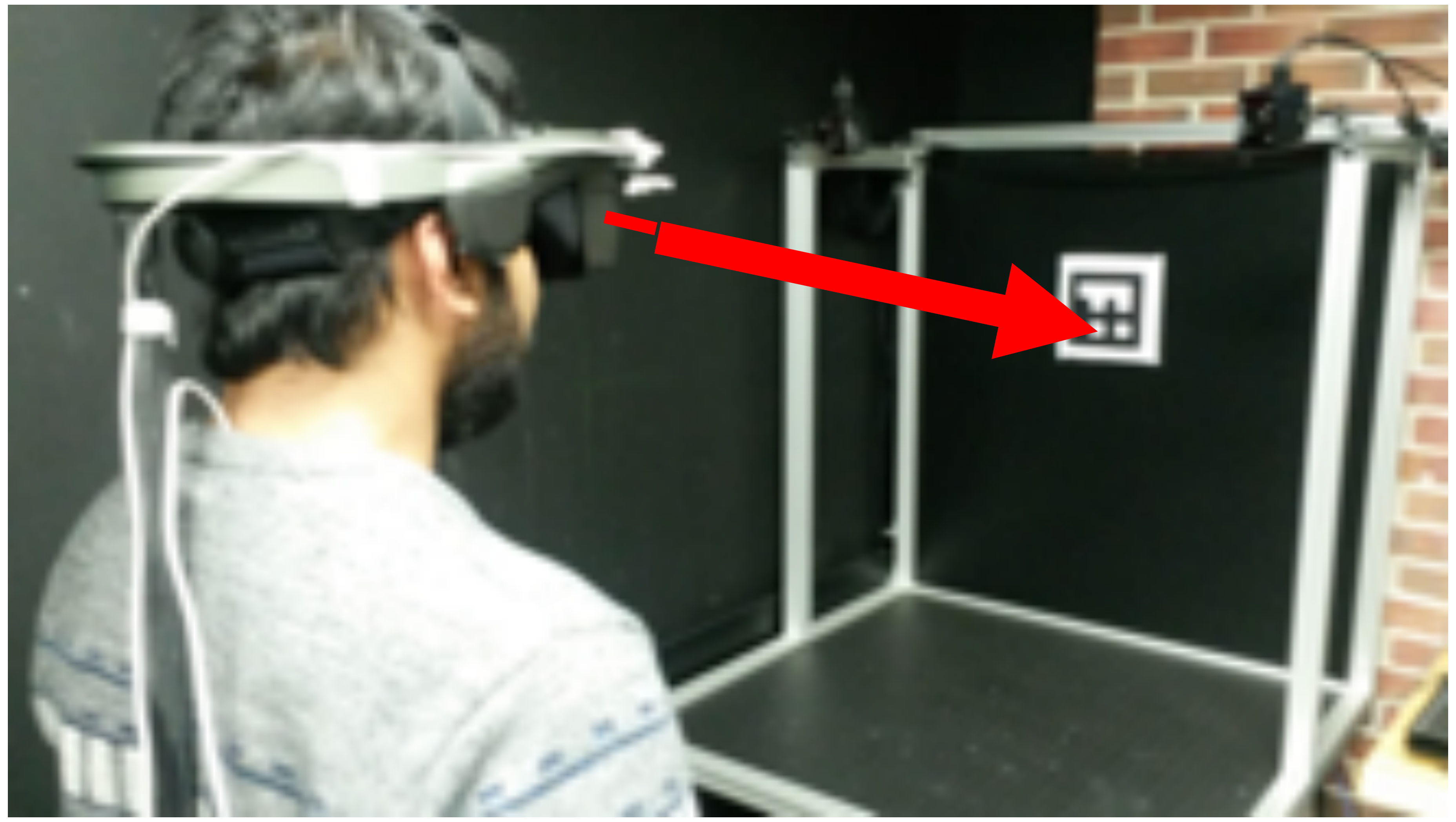
Spatial Calibration

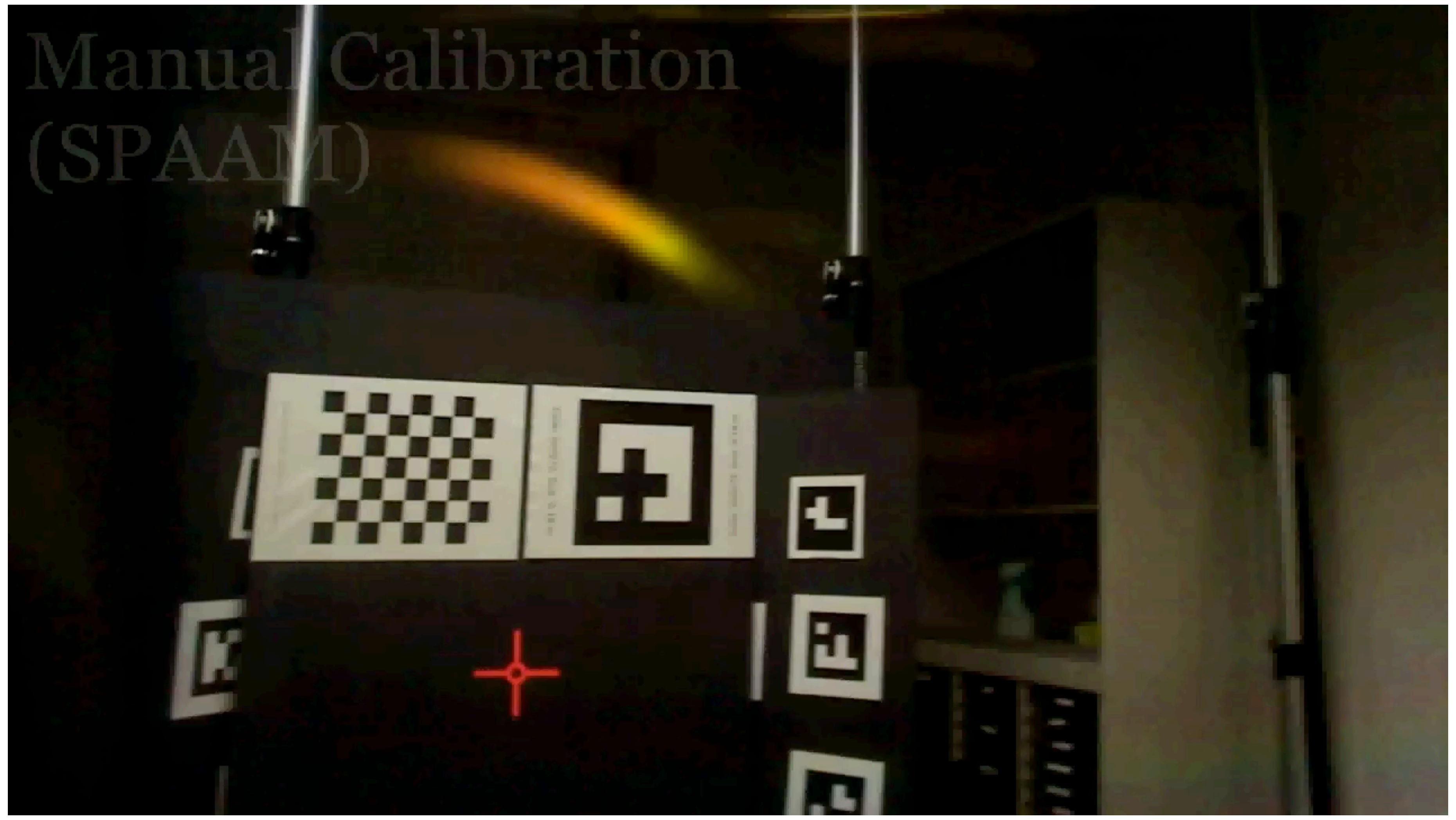


Our eyes and heads are different!



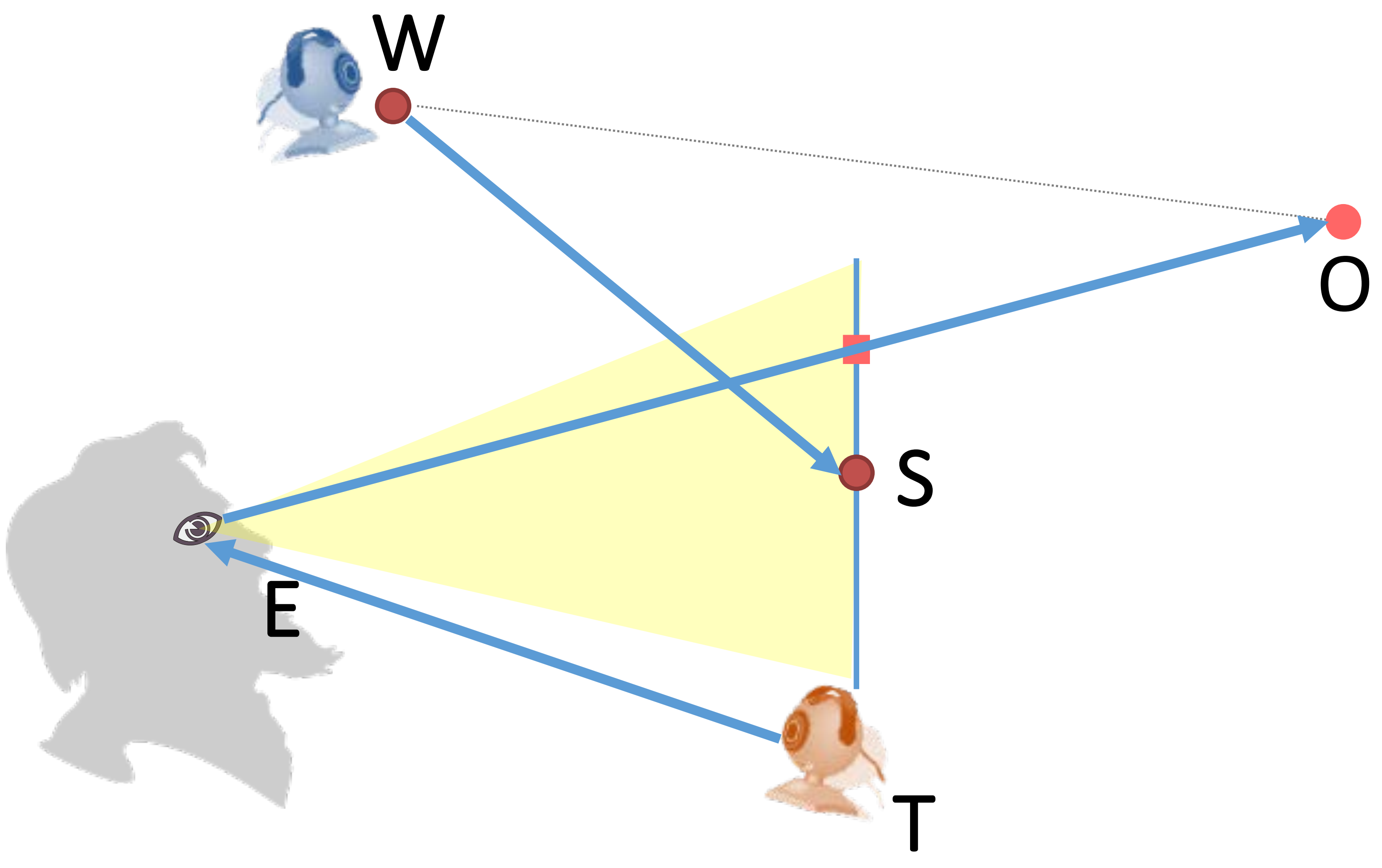


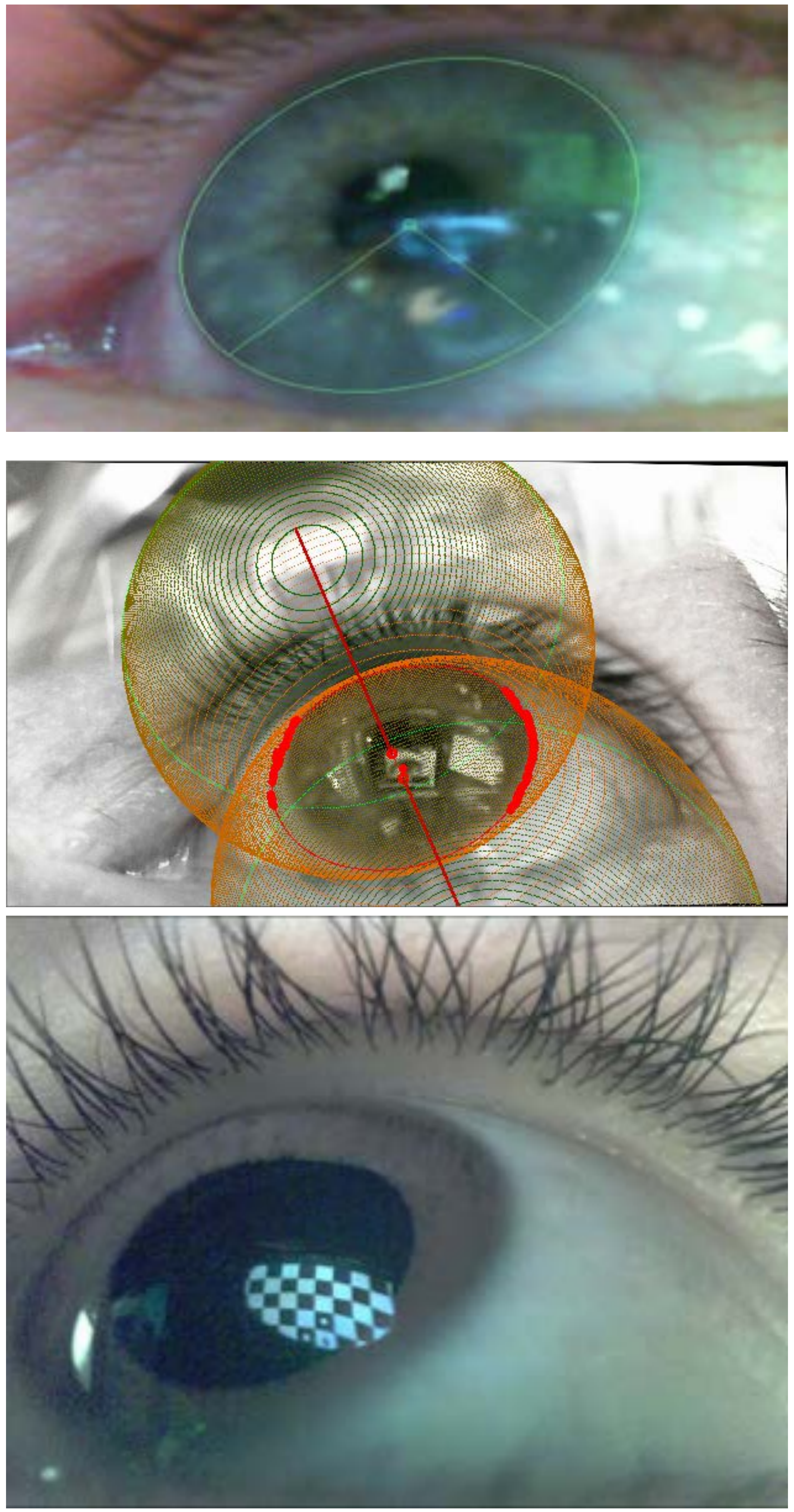




Single Point Active Alignment Method (SPAAM)

- Assumption of simple projective geometry
- Assume:
  Eye=Camera
  Display = Image Plane
- Standard Camera Calibration





Interaction Free Display Calibration

- Assumption of simple projective geometry
- Needs:
  - Eye tracking or eye camera
  - Physical model of the OST-HMD screen
- Compute alignment continuously at runtime

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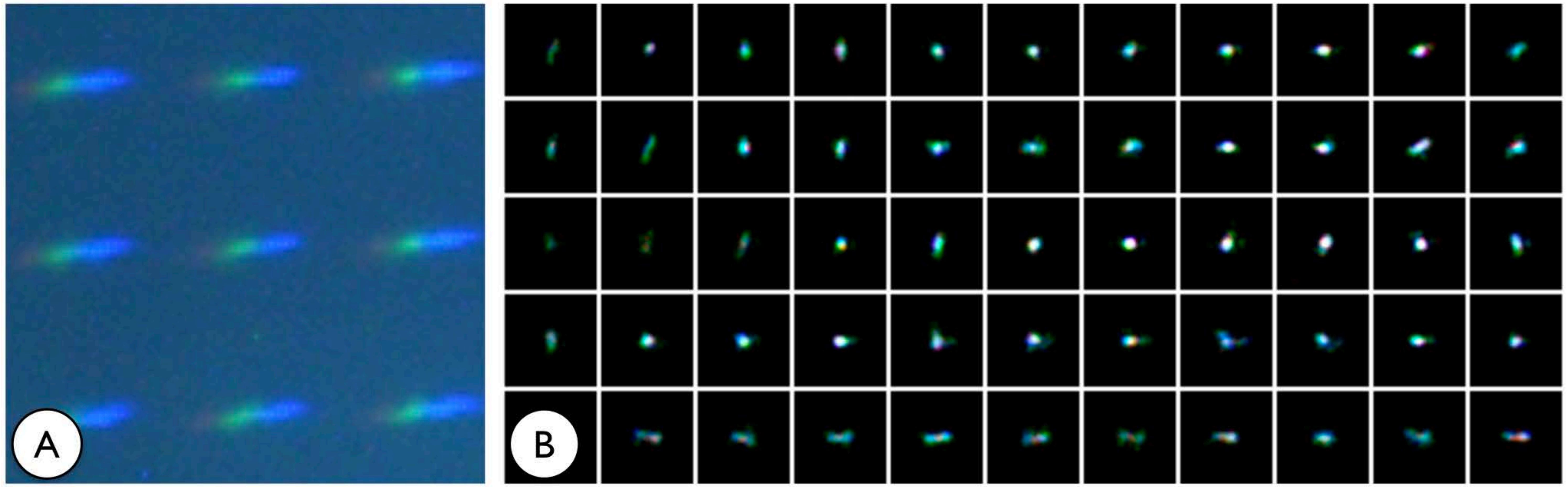
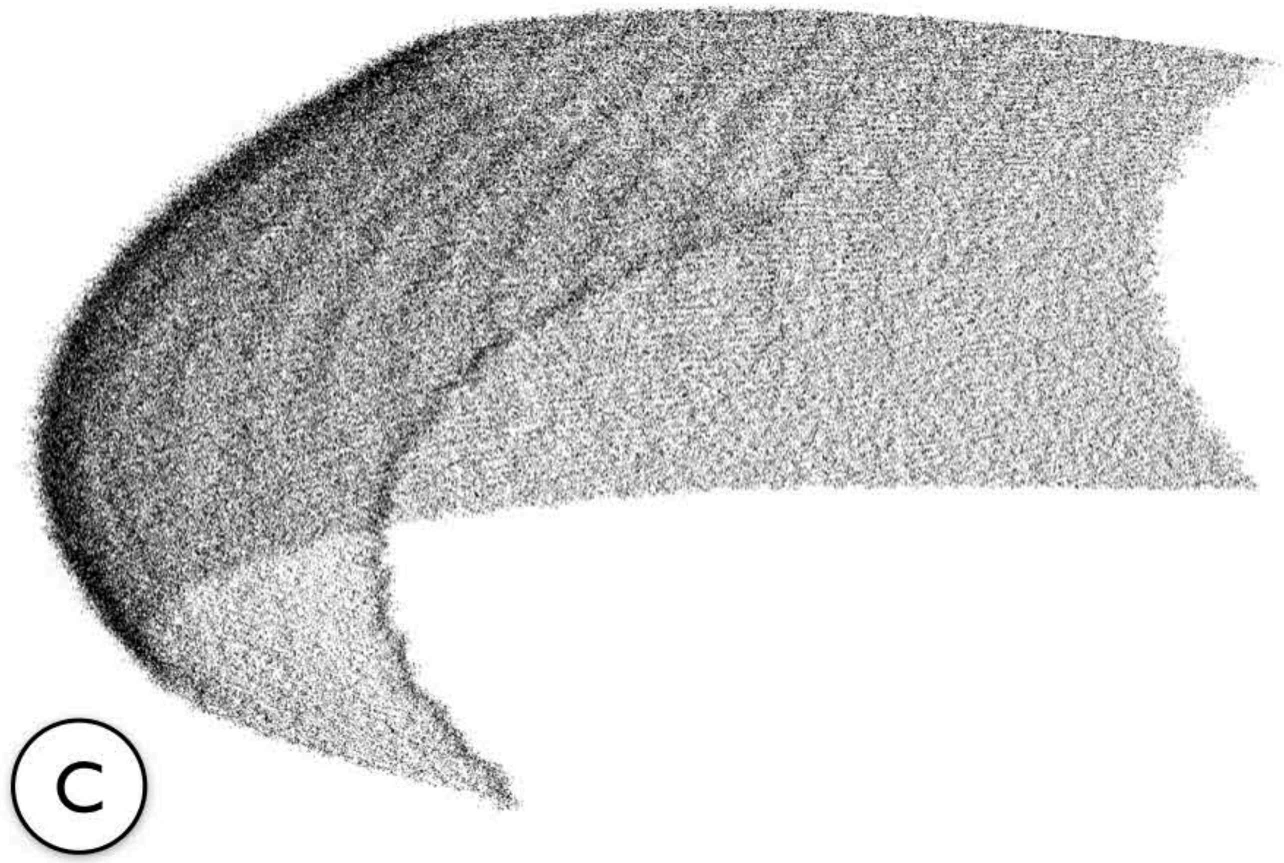
Distortion correction



Hamasaki and Itoh “Varifocal occlusion for optical see-through head-mounted displays using a slide occlusion mask” [44]



Klemm et al. “Non-parametric Camera-Based Calibration of Optical See-Through Glasses for AR Applications” [79]

Temporal Realism

Vs.

- Latency well researched in related fields
  - Cause for simulator sickness
  - VR studies showed perceivable latency below 5ms [63]
  - HCI studies showed perceivable latency lower than 17ms [64]
  - User performance affected by latency as low as 2.38ms [115]

ARIVE

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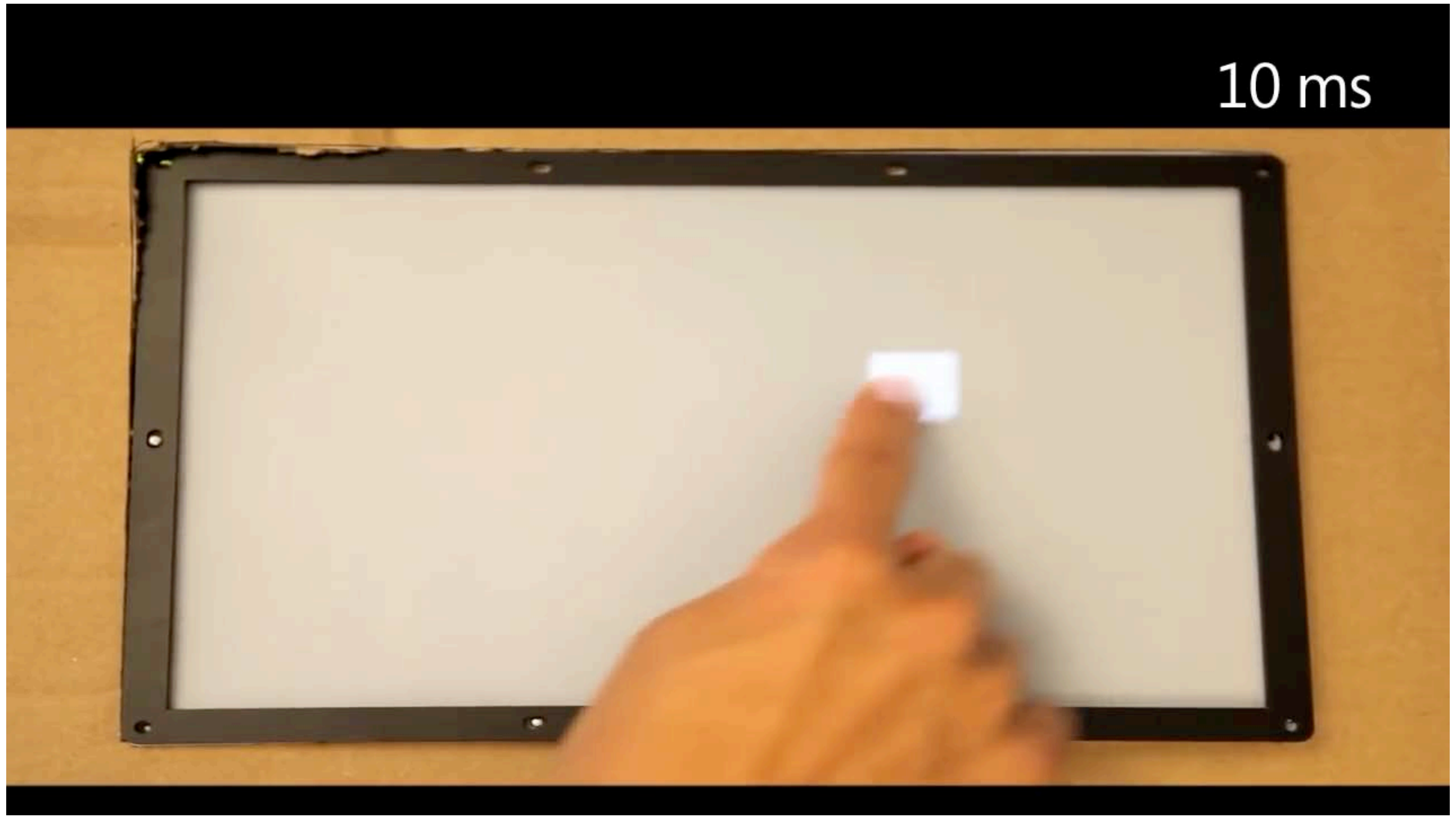

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- Critical Flicker frequency
  - Non-uniform but often provided as approximately 90 Hz [10]
  - Specific patterns allow people to perceived flicker at 500Hz [27]

ARIVE

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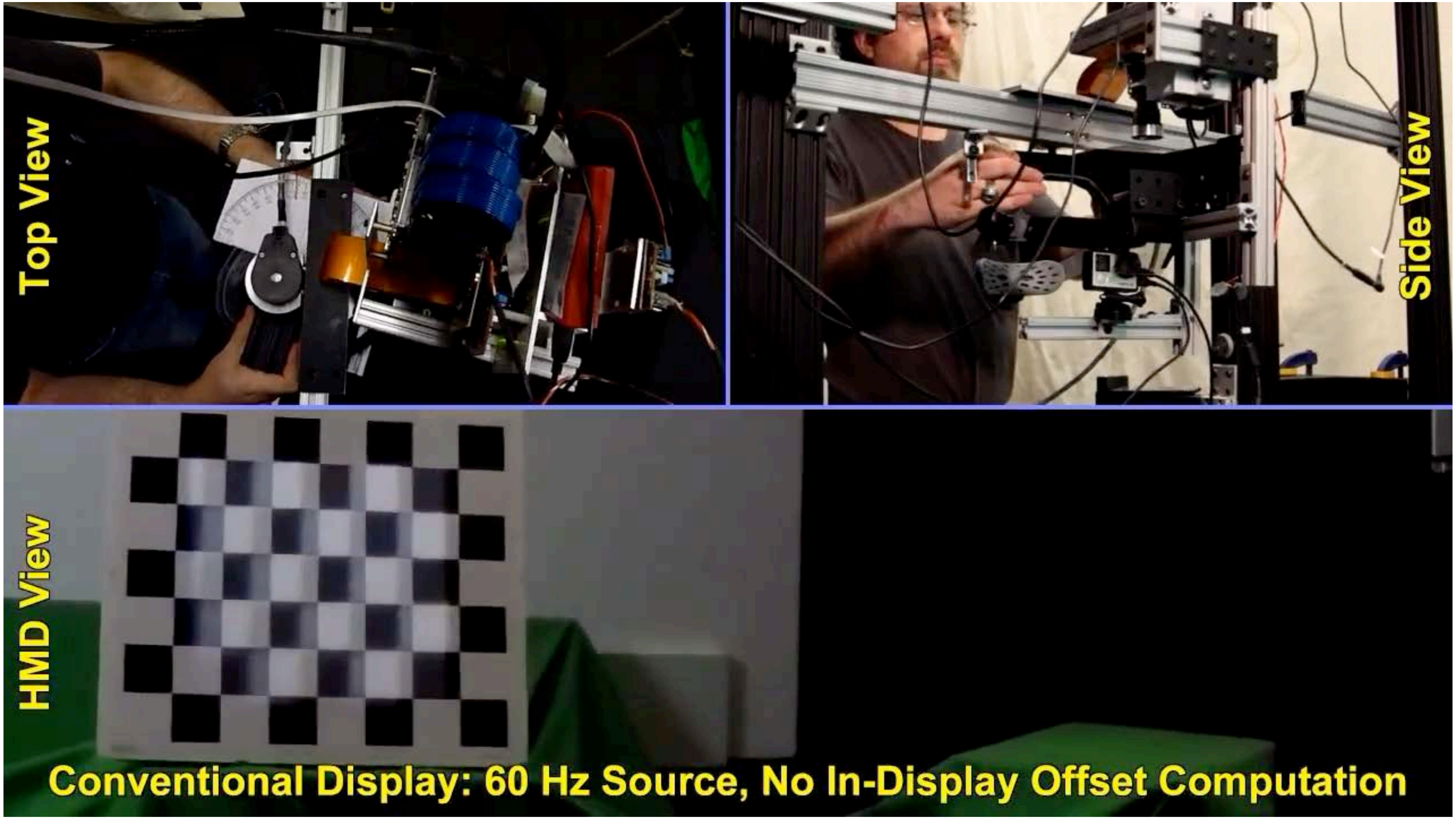
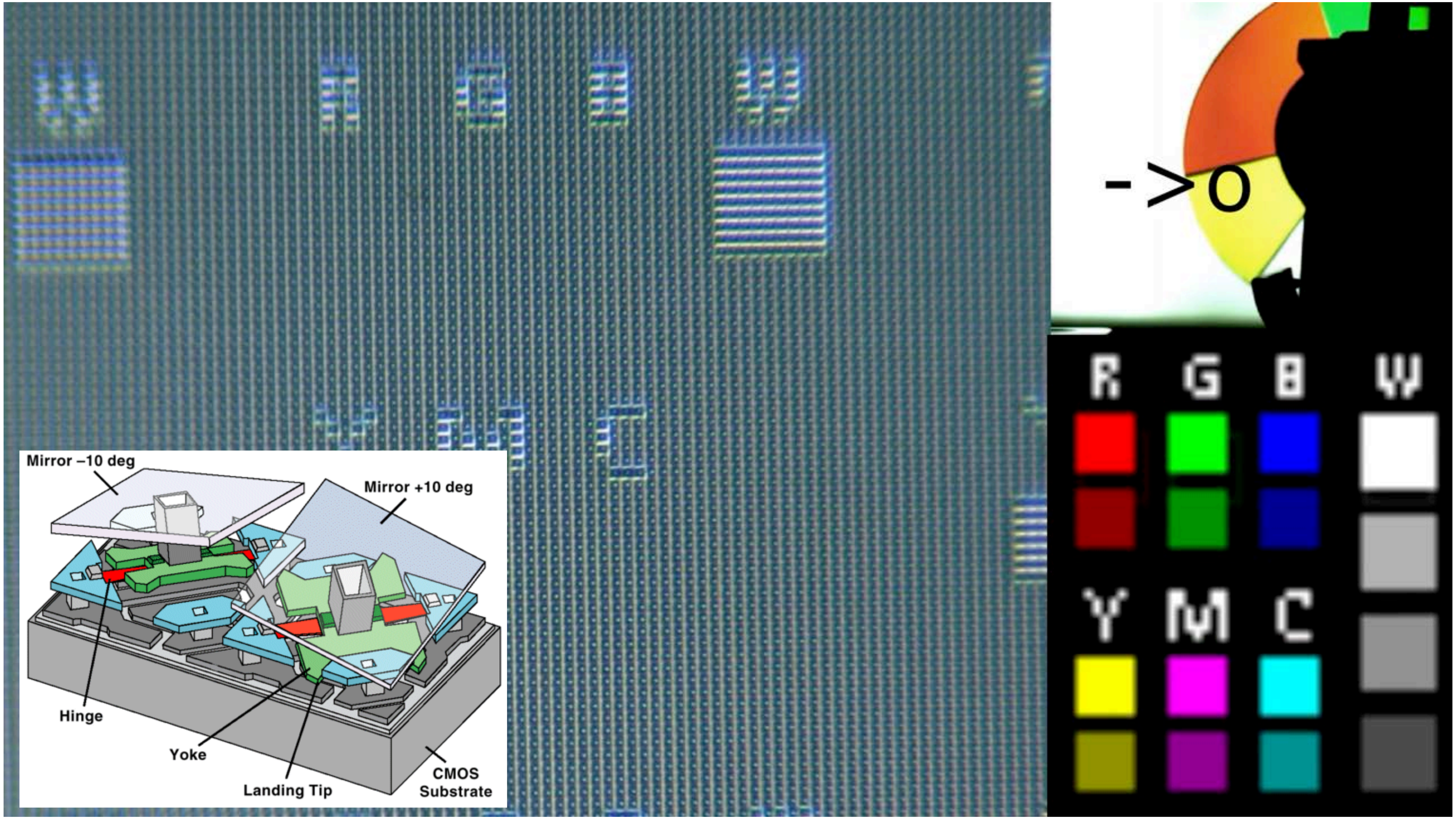
- Critical Flicker frequency
  - Non-uniform but often provided as approximately 90 Hz [10]
  - Specific patterns allow people to perceived flicker at 500Hz [27]
- MS Hololens 60Hz update rate, approx. 15ms display latency



Lincoln et al. "*From Motion to Photons in 80 Microseconds: Towards Minimal Latency for Virtual and Augmented Reality*" [99]

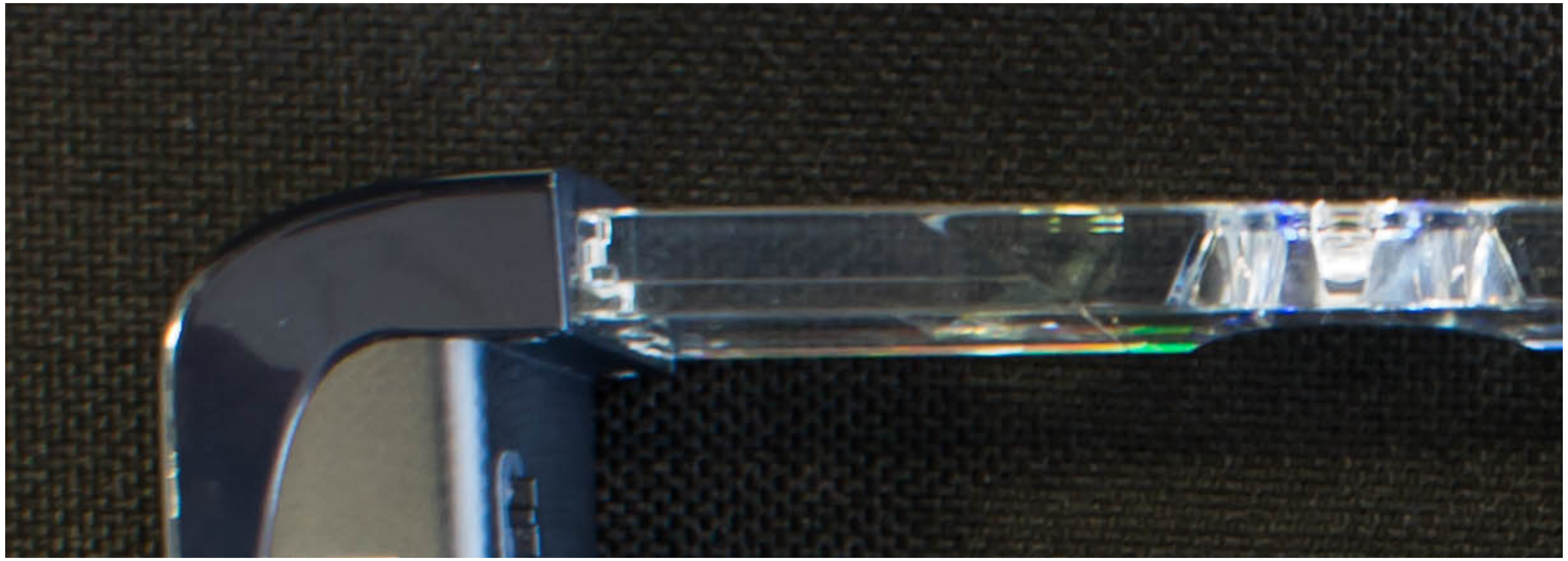
ARIVE

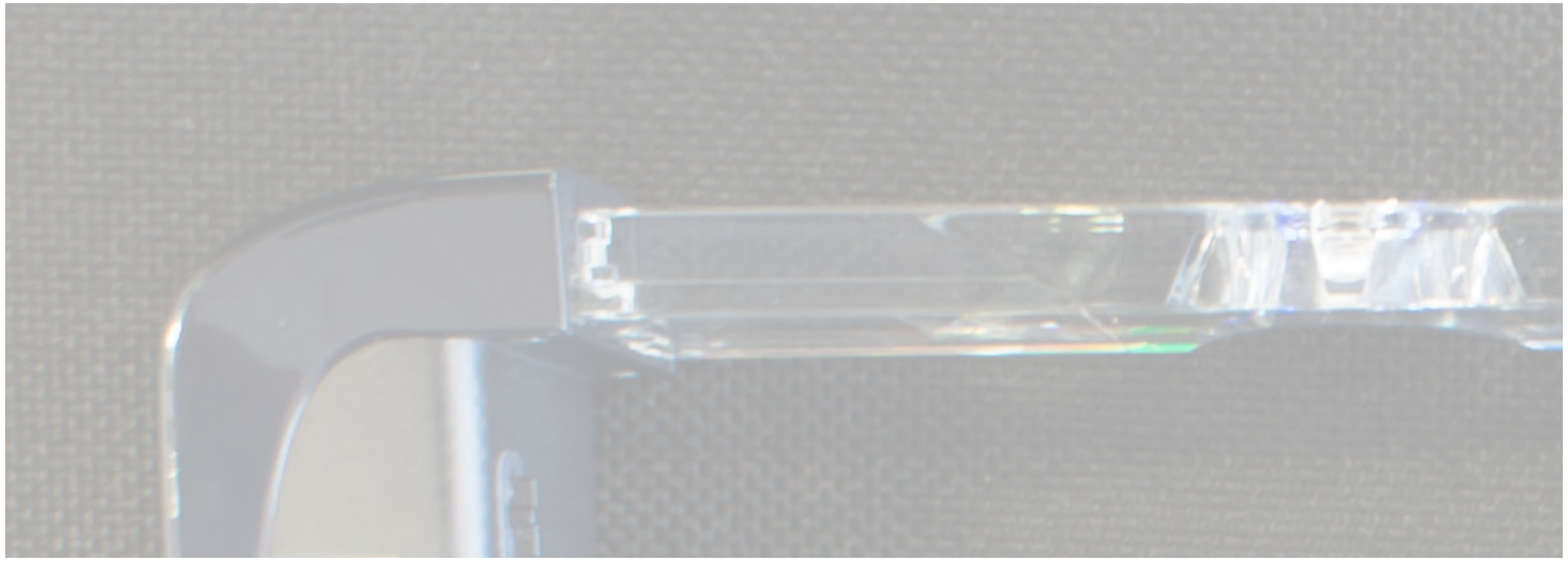


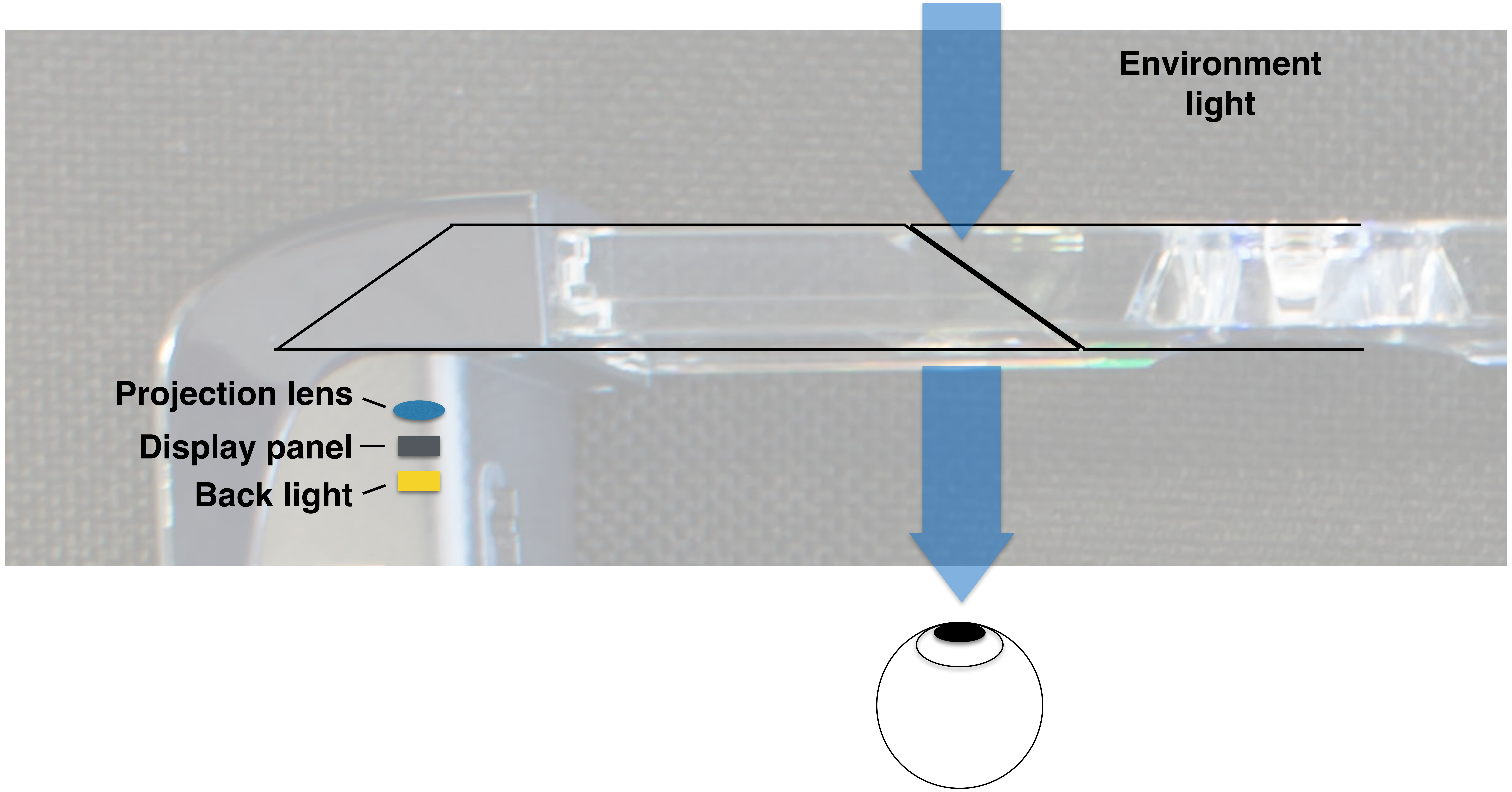
YouTube “DMD-mirrors of a DLP-projector moving in slow motion”

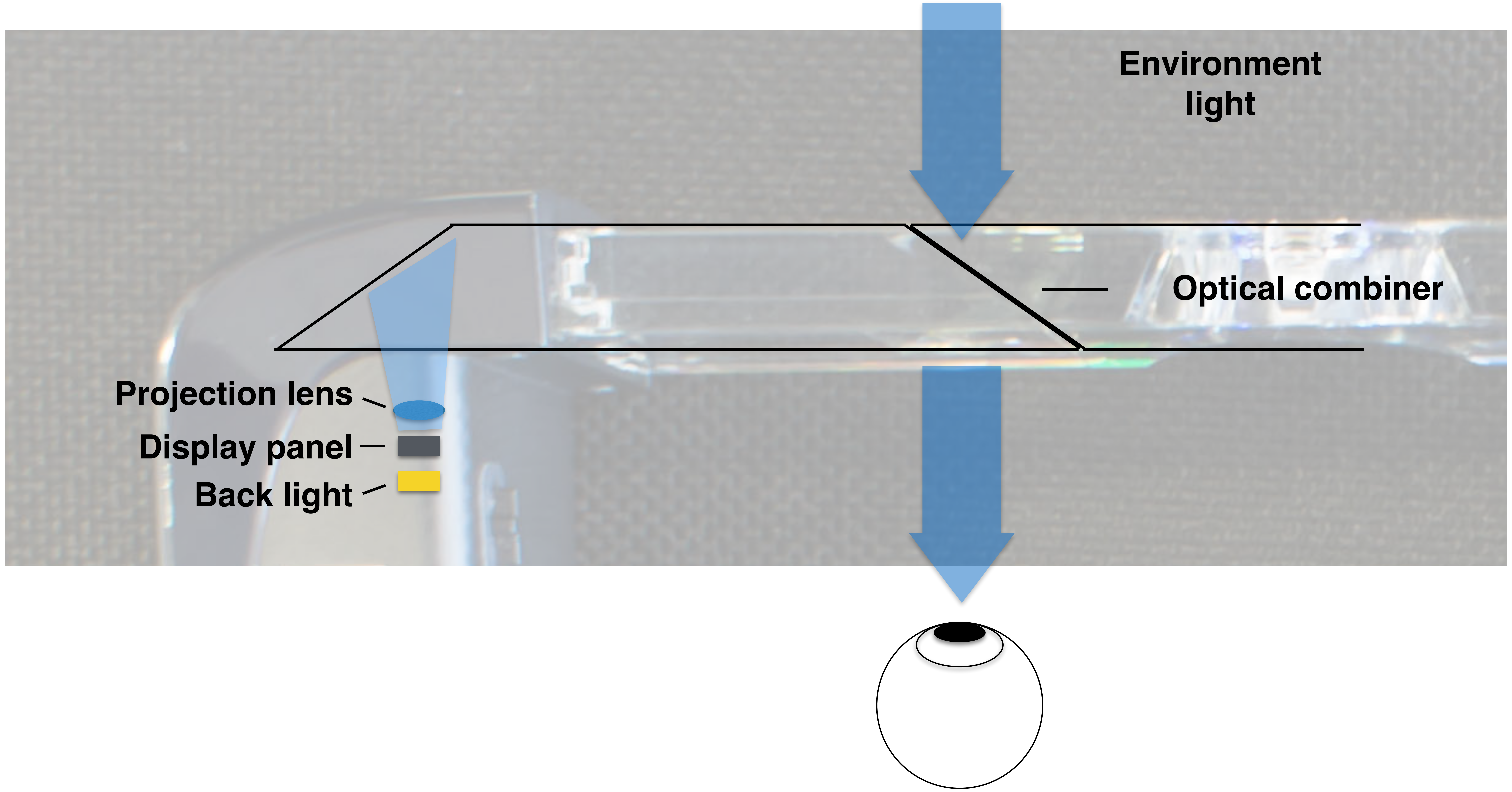
Visual Realism

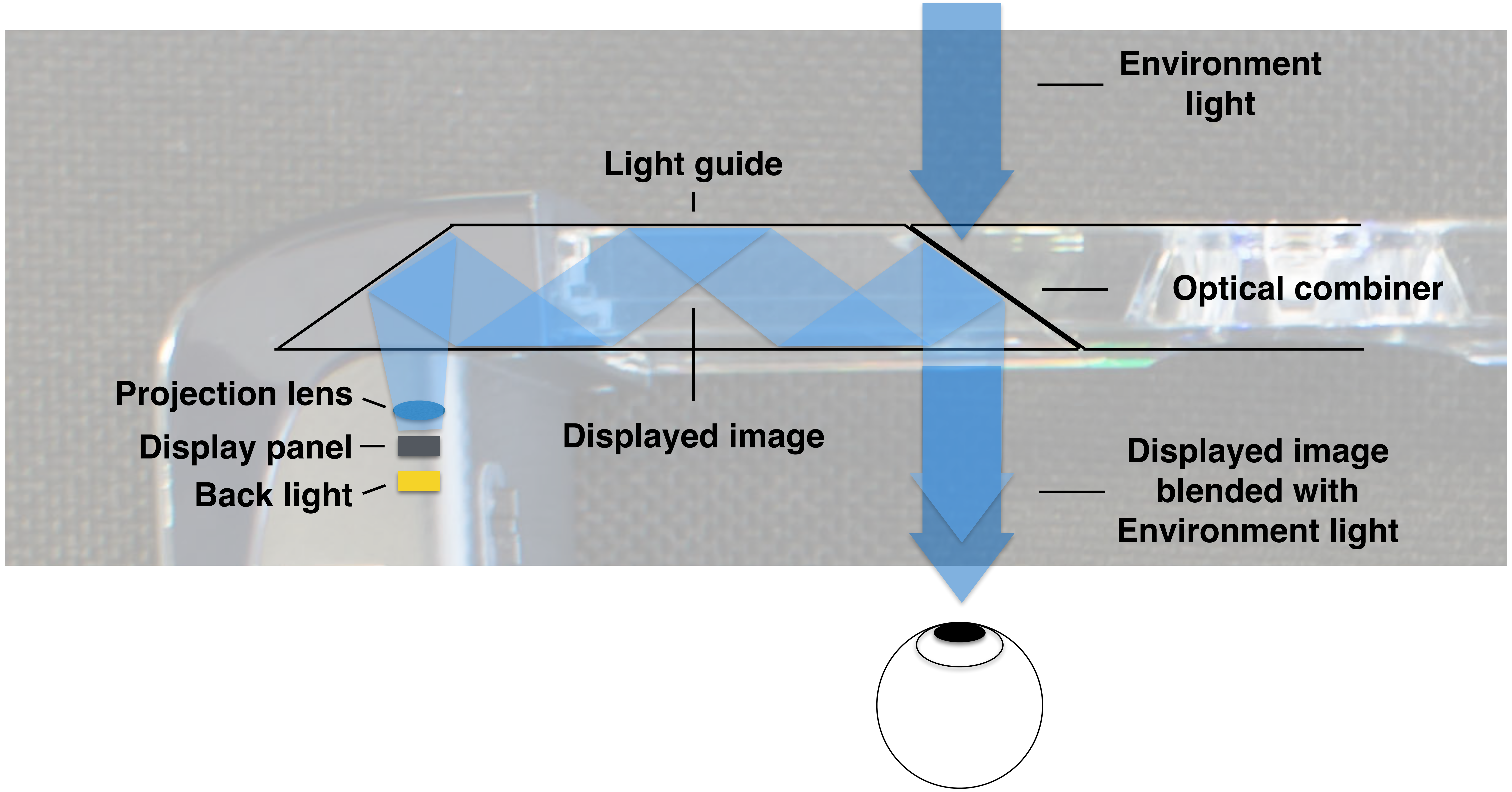
Visual Realism:
Colour

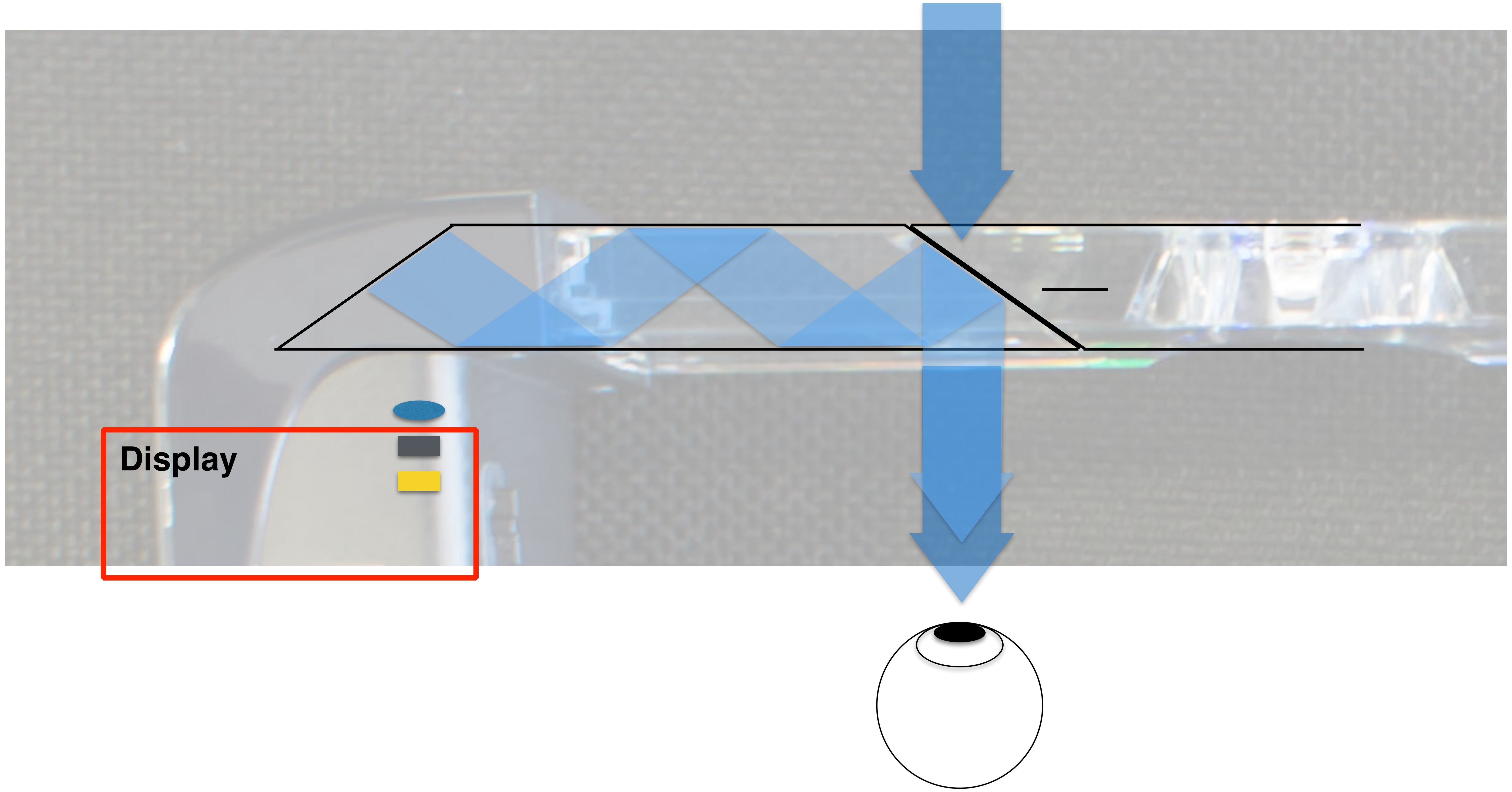




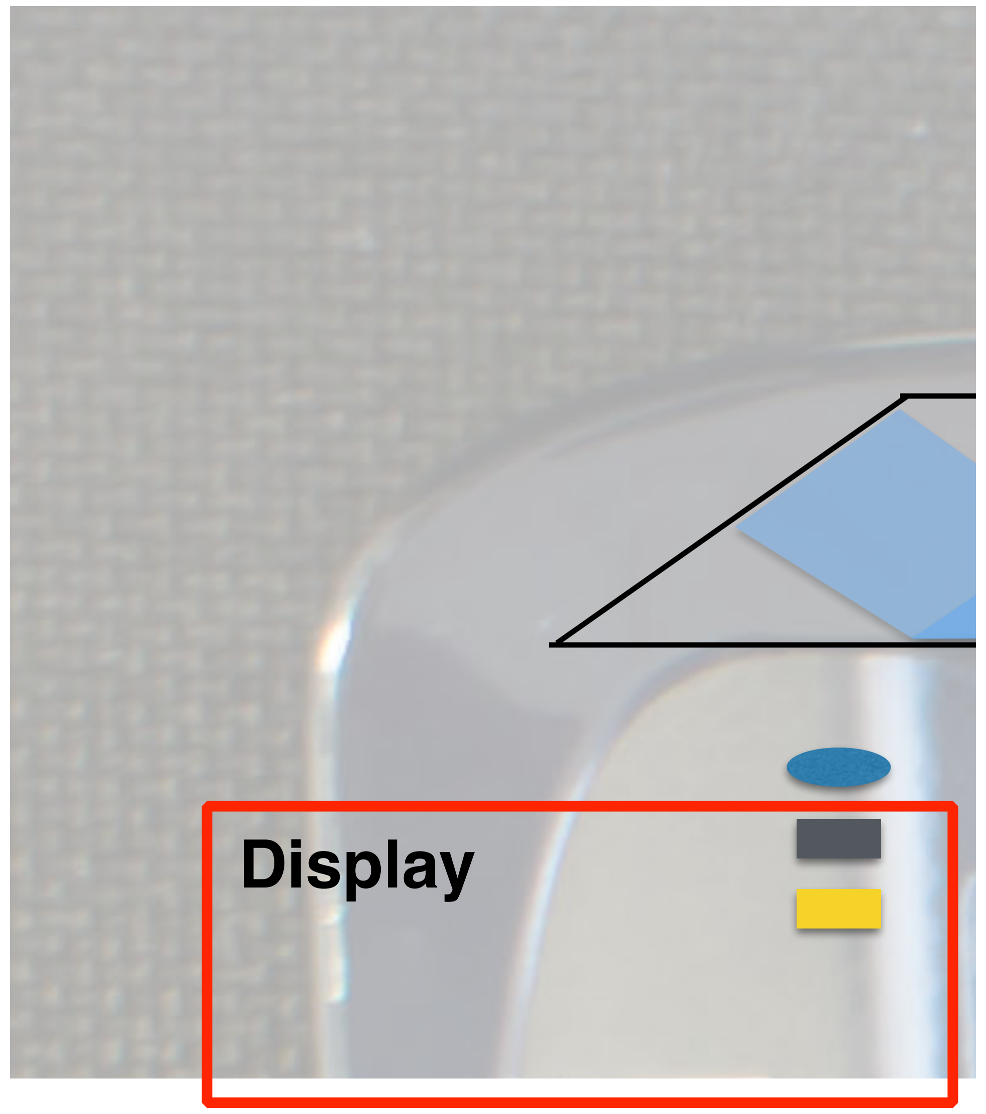

Environment
light
Projection lens
Display panel
Back light

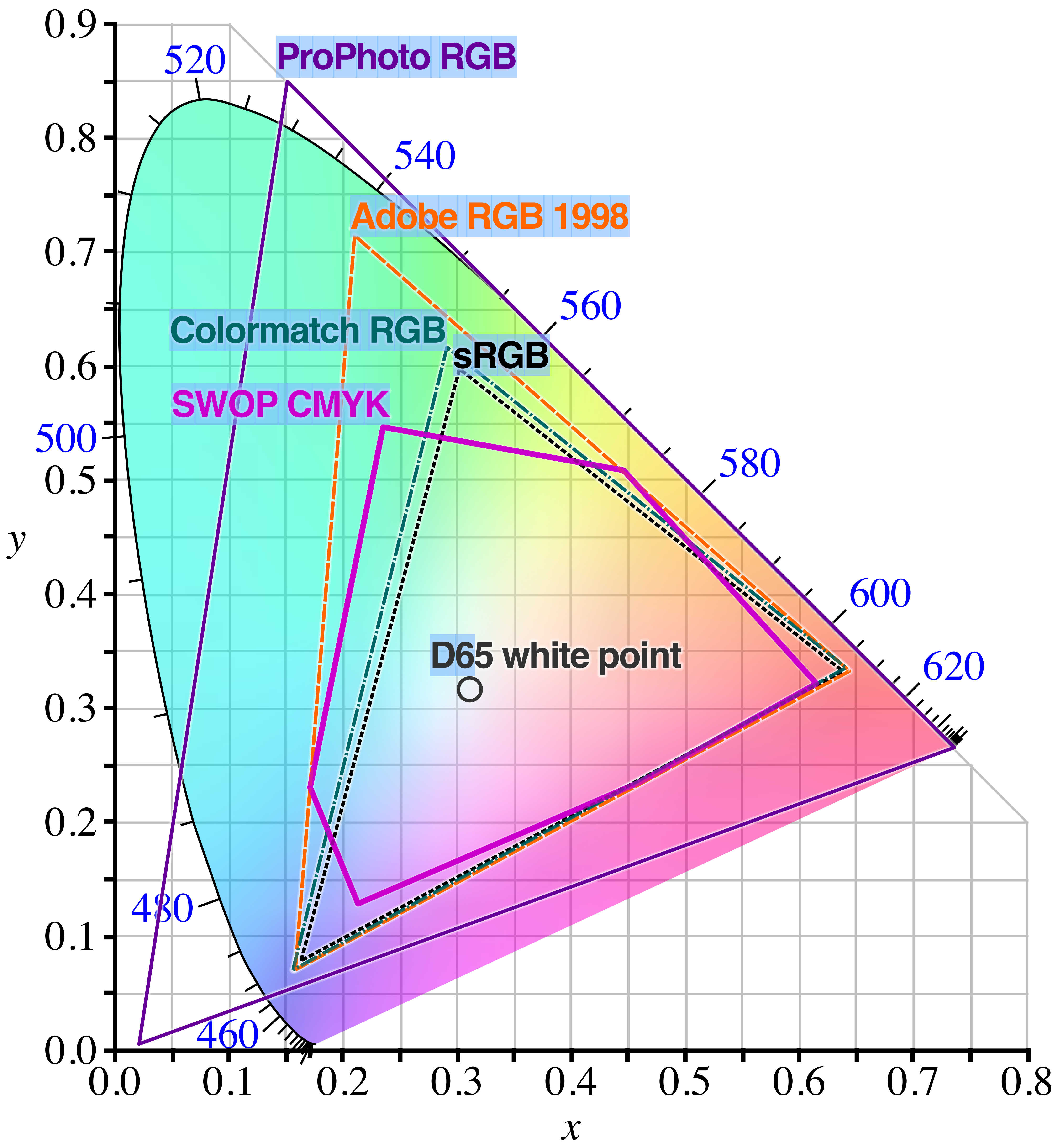

Environment light
Optical combiner
Projection lens
Display panel
Back light


Environment light
Light guide
Optical combiner
Projection lens
Display panel
Back light
Displayed image
Displayed image blended with Environment light

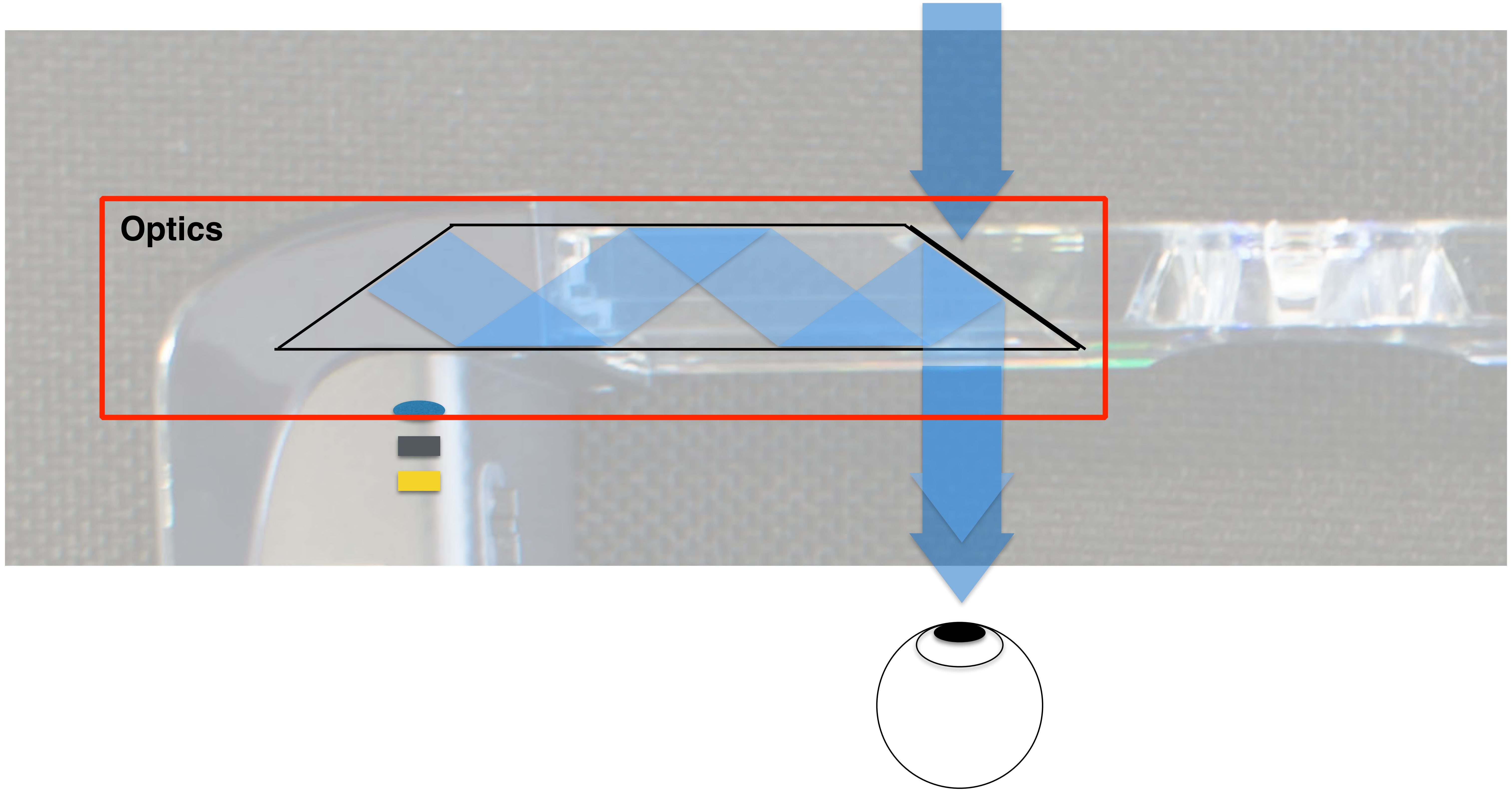

Display

ARIVE

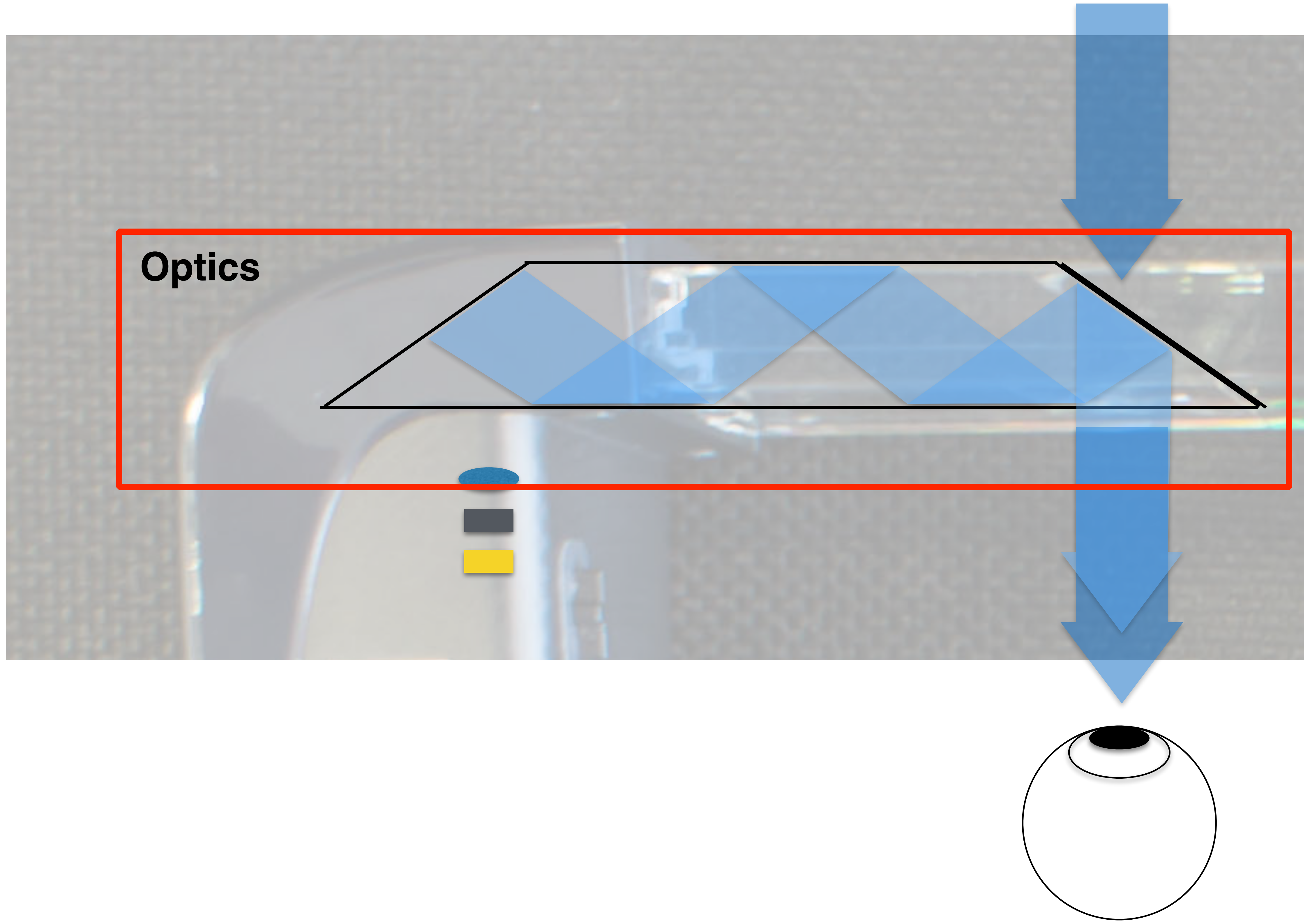

Display

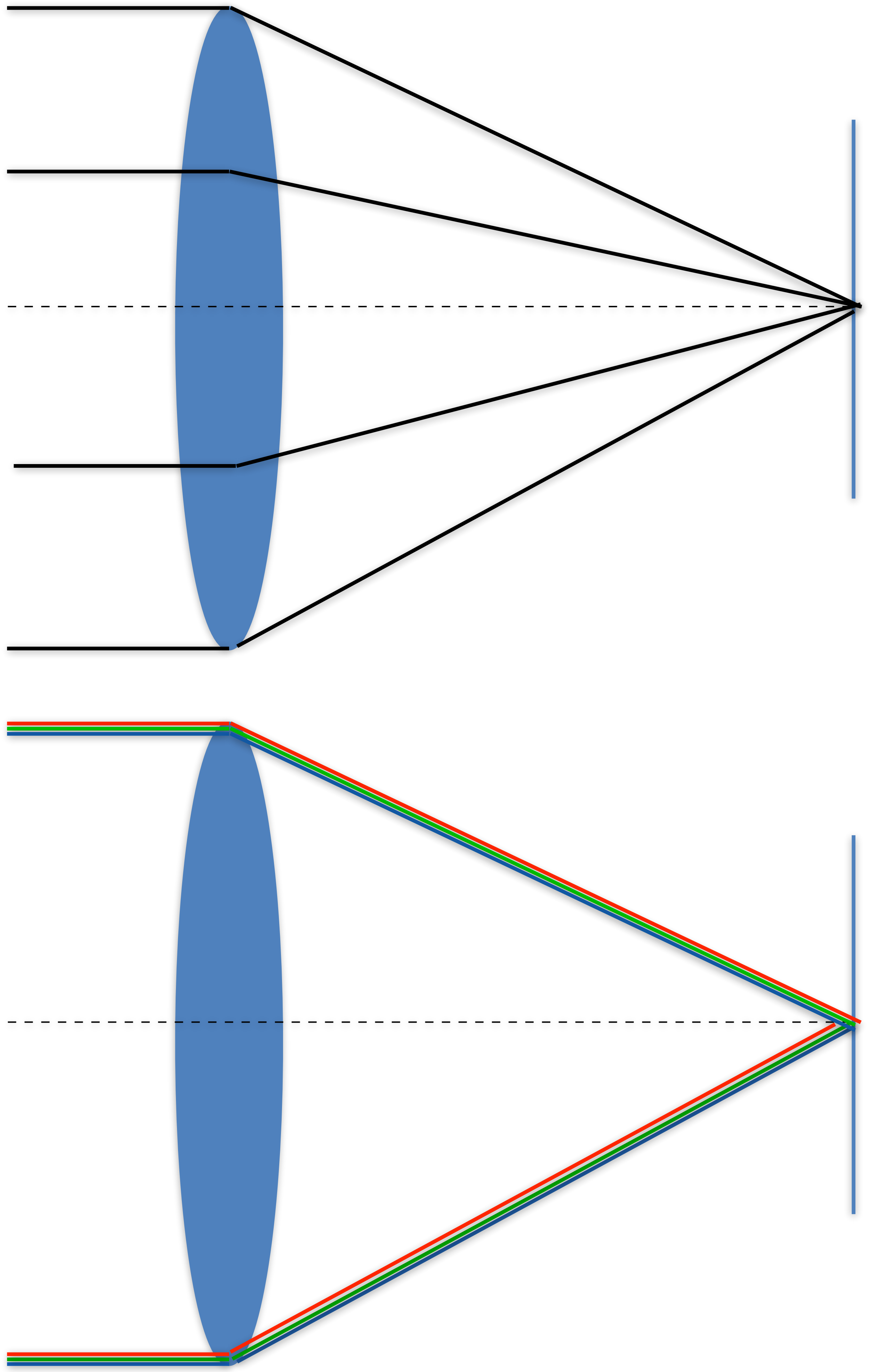

ProPhoto RGB
Adobe RGB 1998
Colormatch RGB
sRGB
SWOP CMYK
D65 white point
520
540
560
580
600
620
500
480
460
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
y
x

Itoh et al. "*Semi-Parametric Color Reproduction Method for Optical See-Through Head-Mounted Displays*" [52]

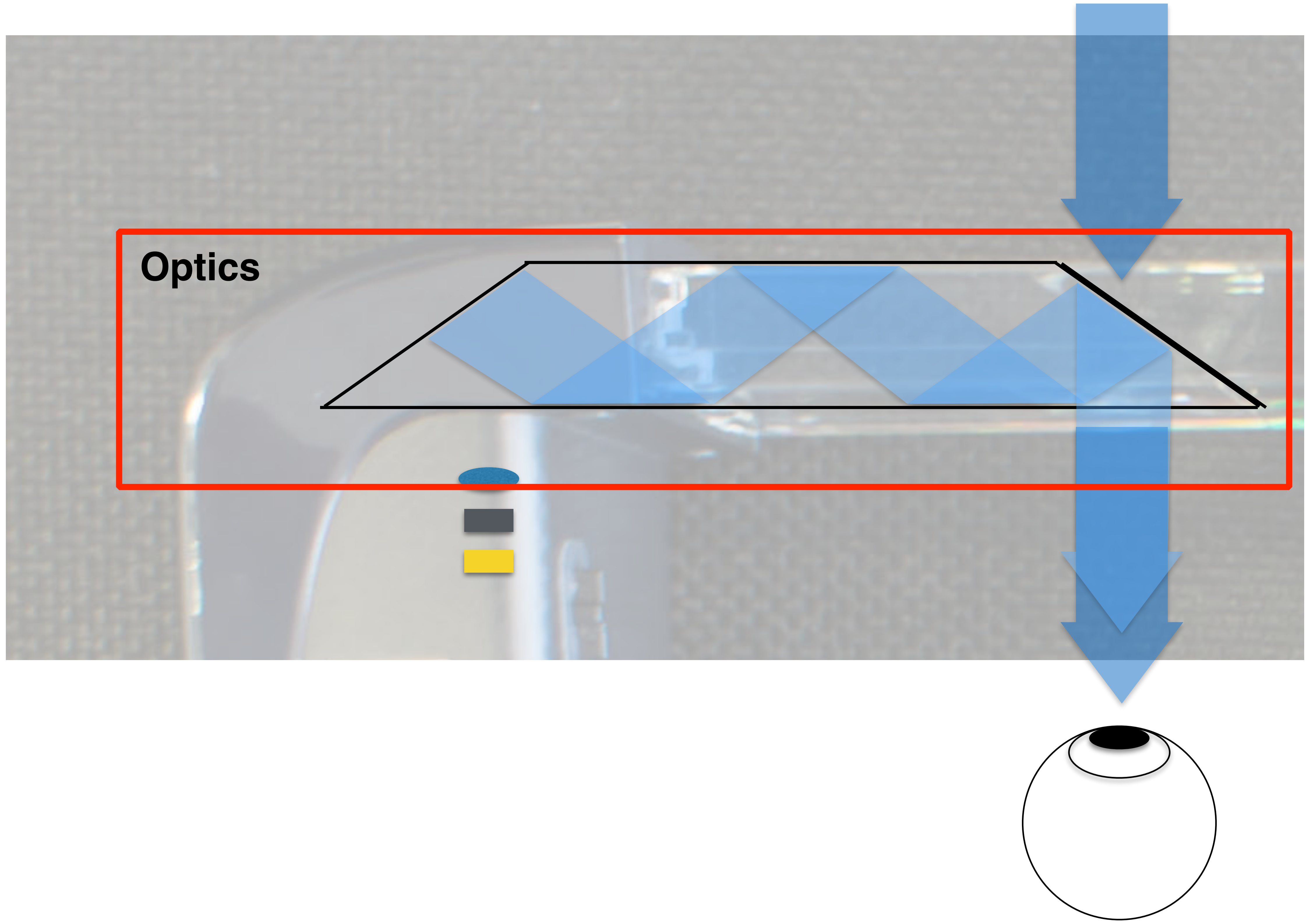

Optics

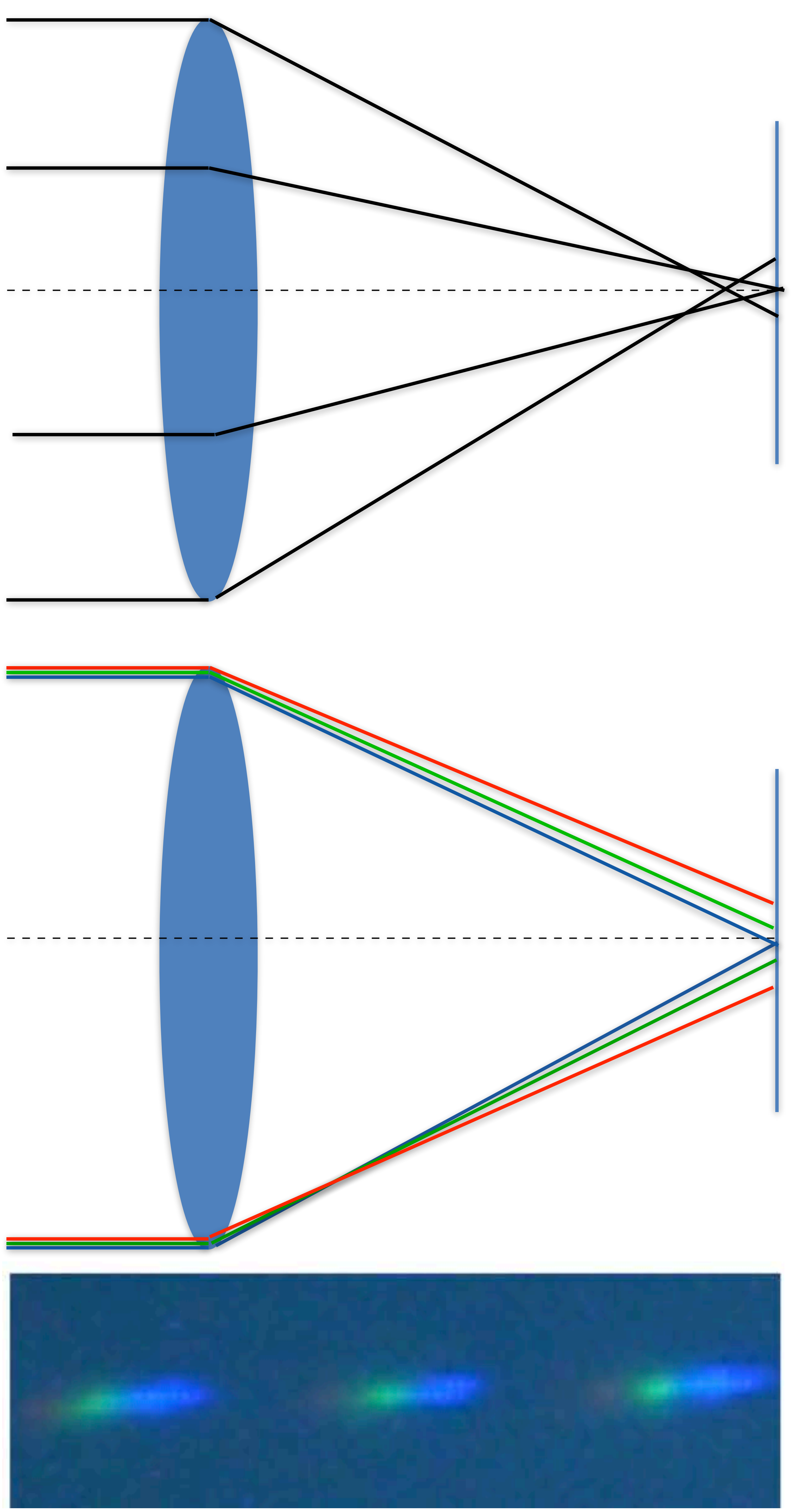
Abberations

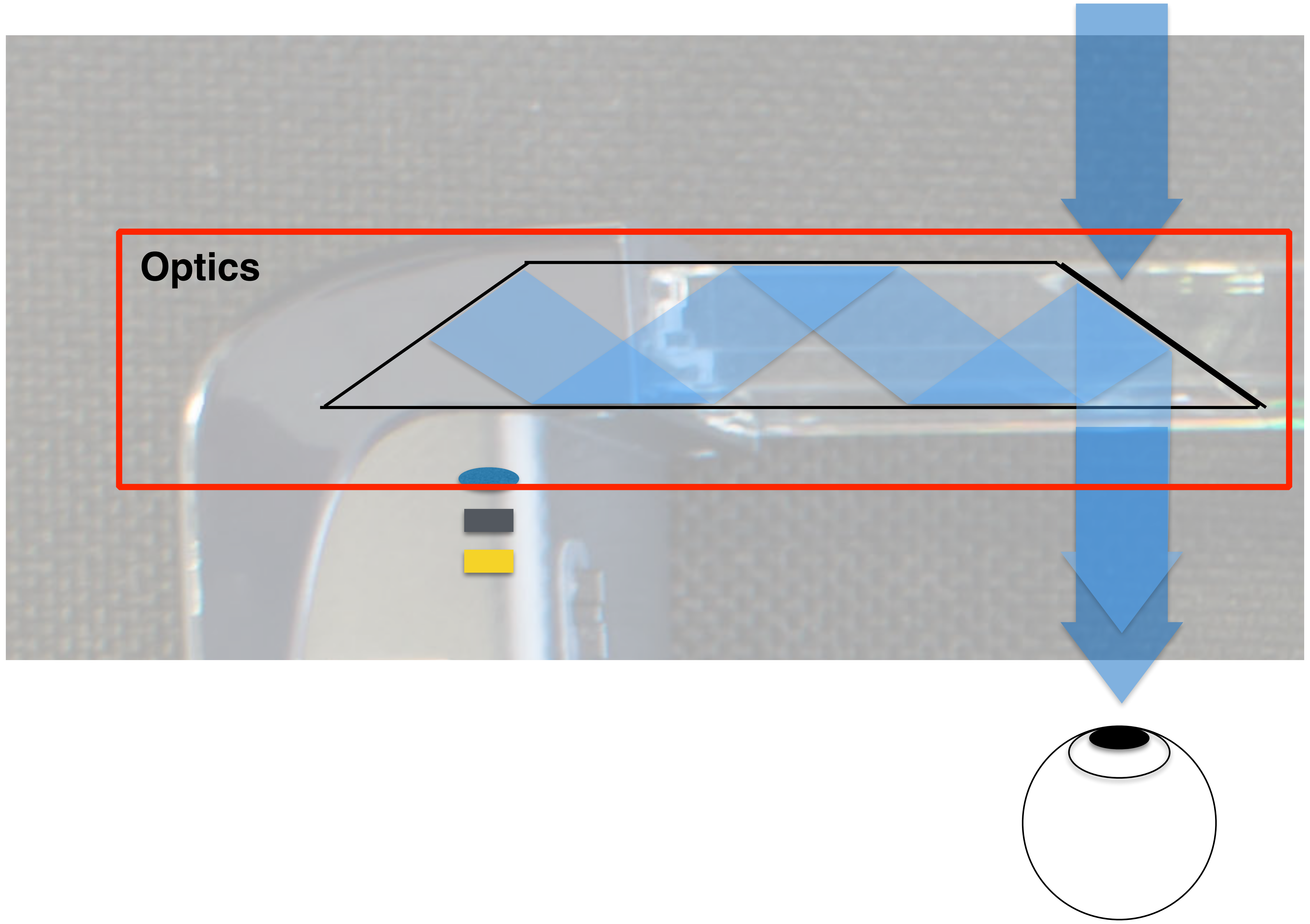




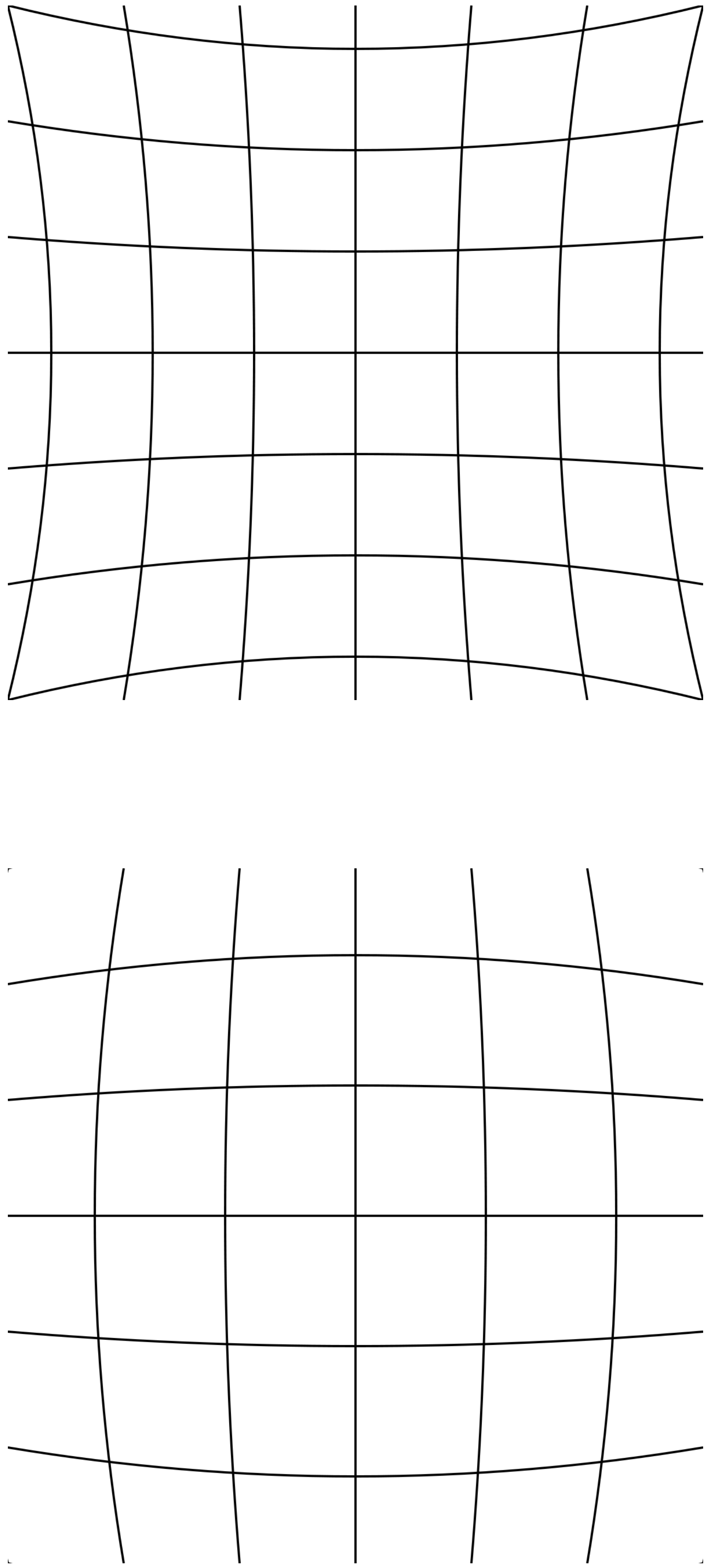
ARIVE

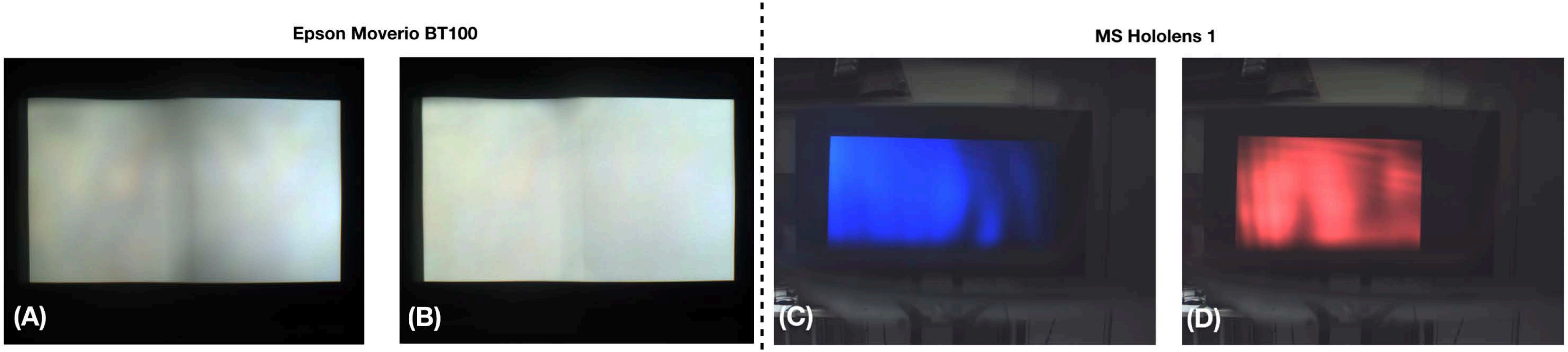






Distorsions





These effects are highly view dependent!

Image courtesy of Karl Guttag: www.kguttag.com

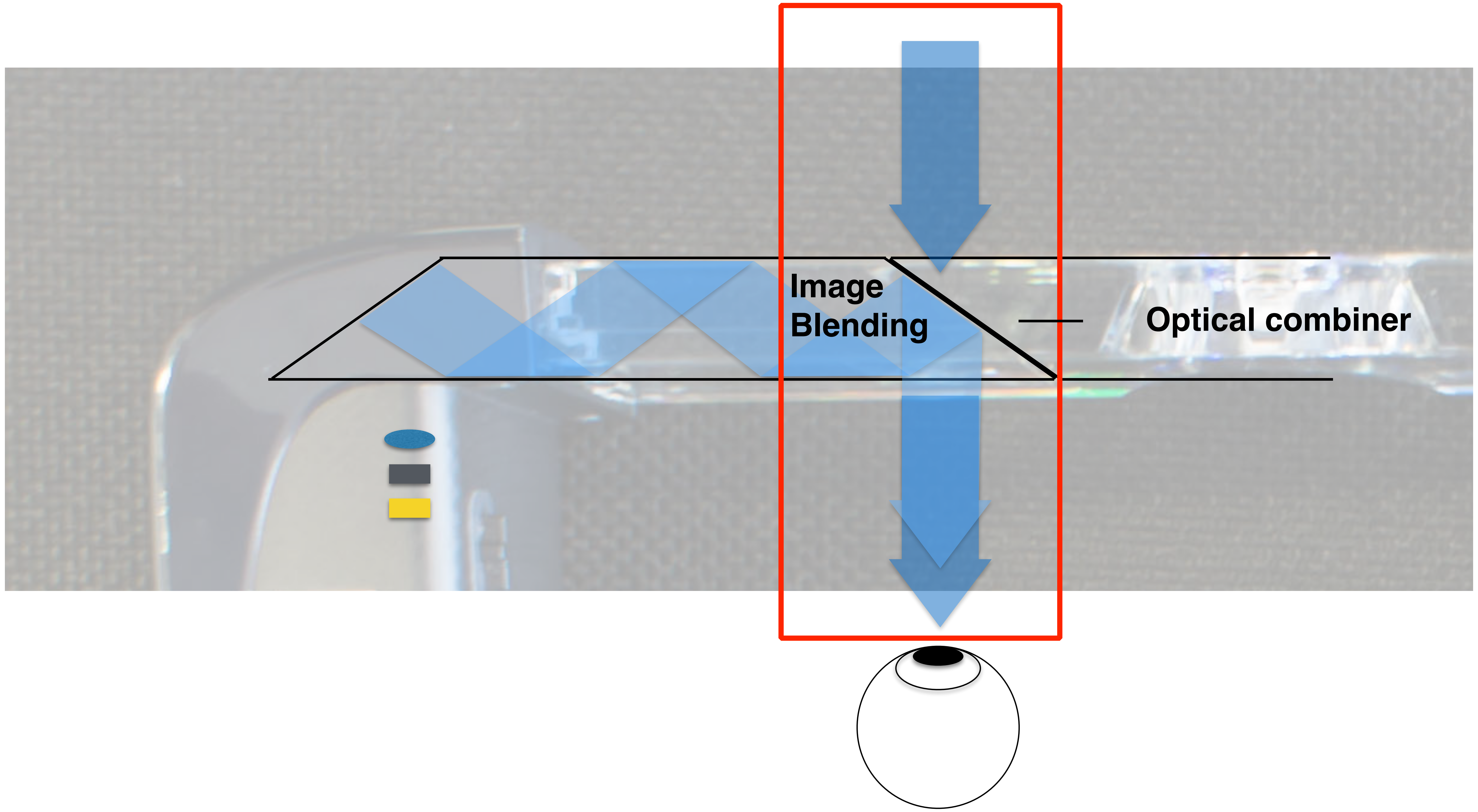
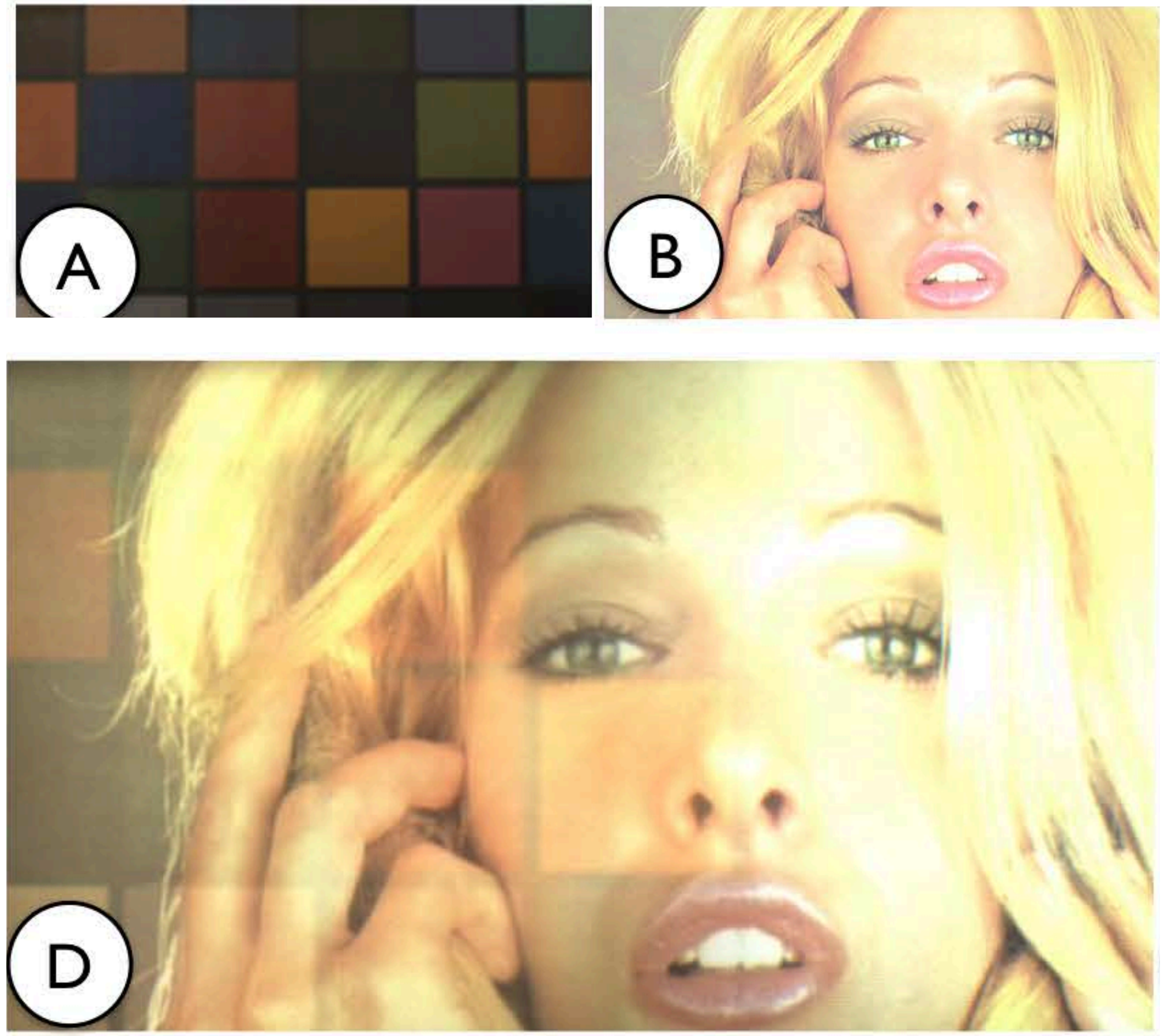


Image
Blending
Optical combiner


A
B
D

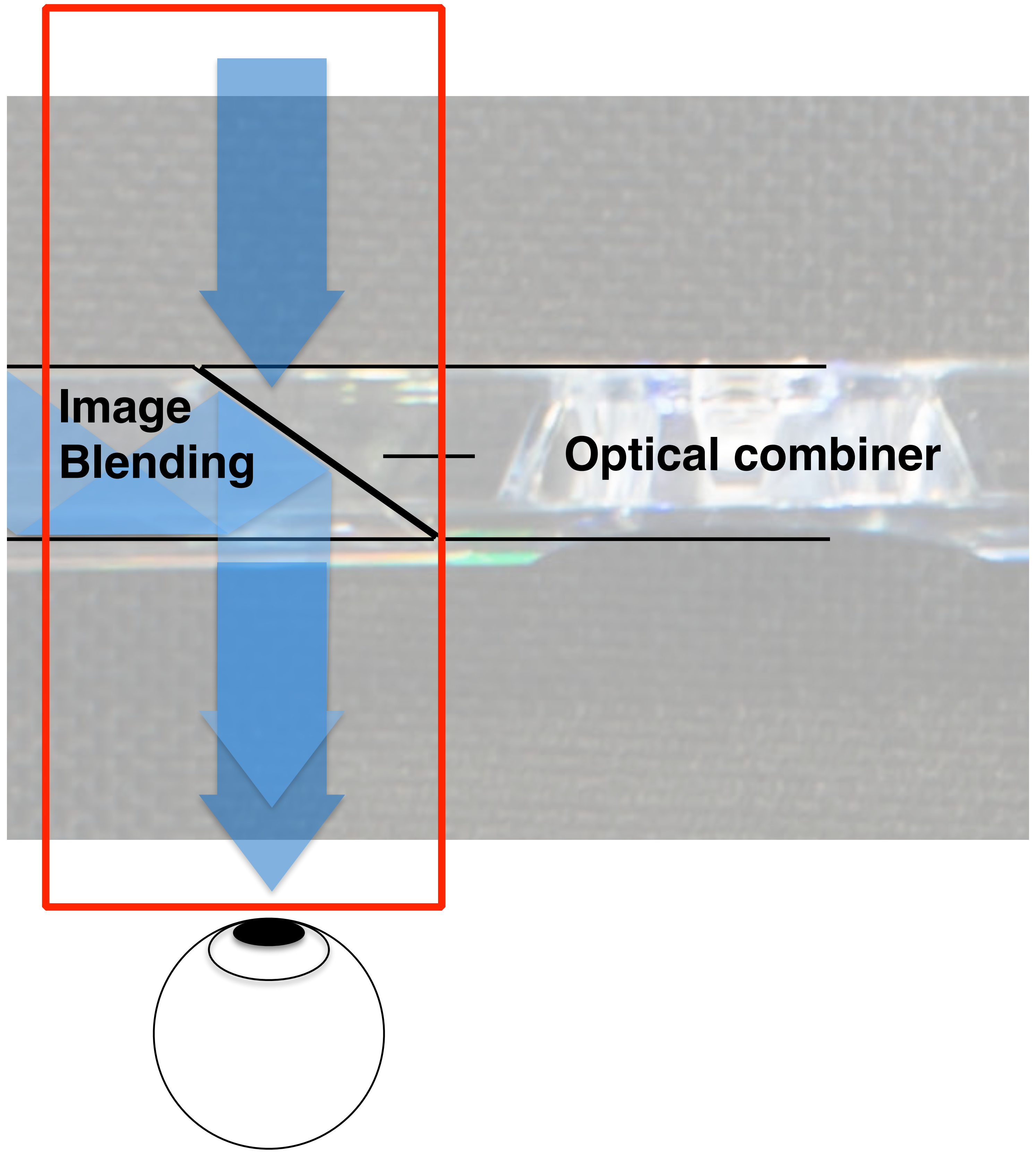
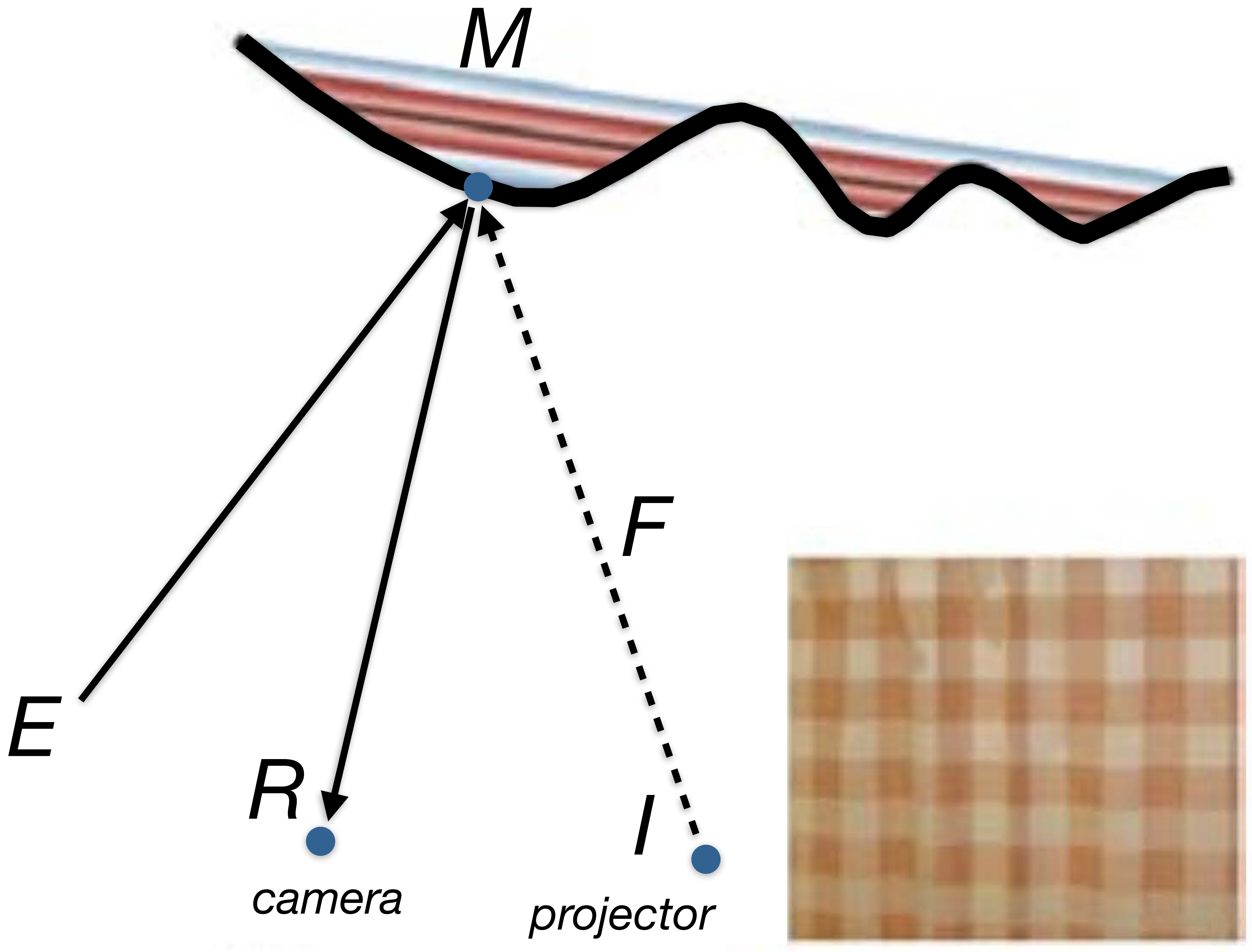


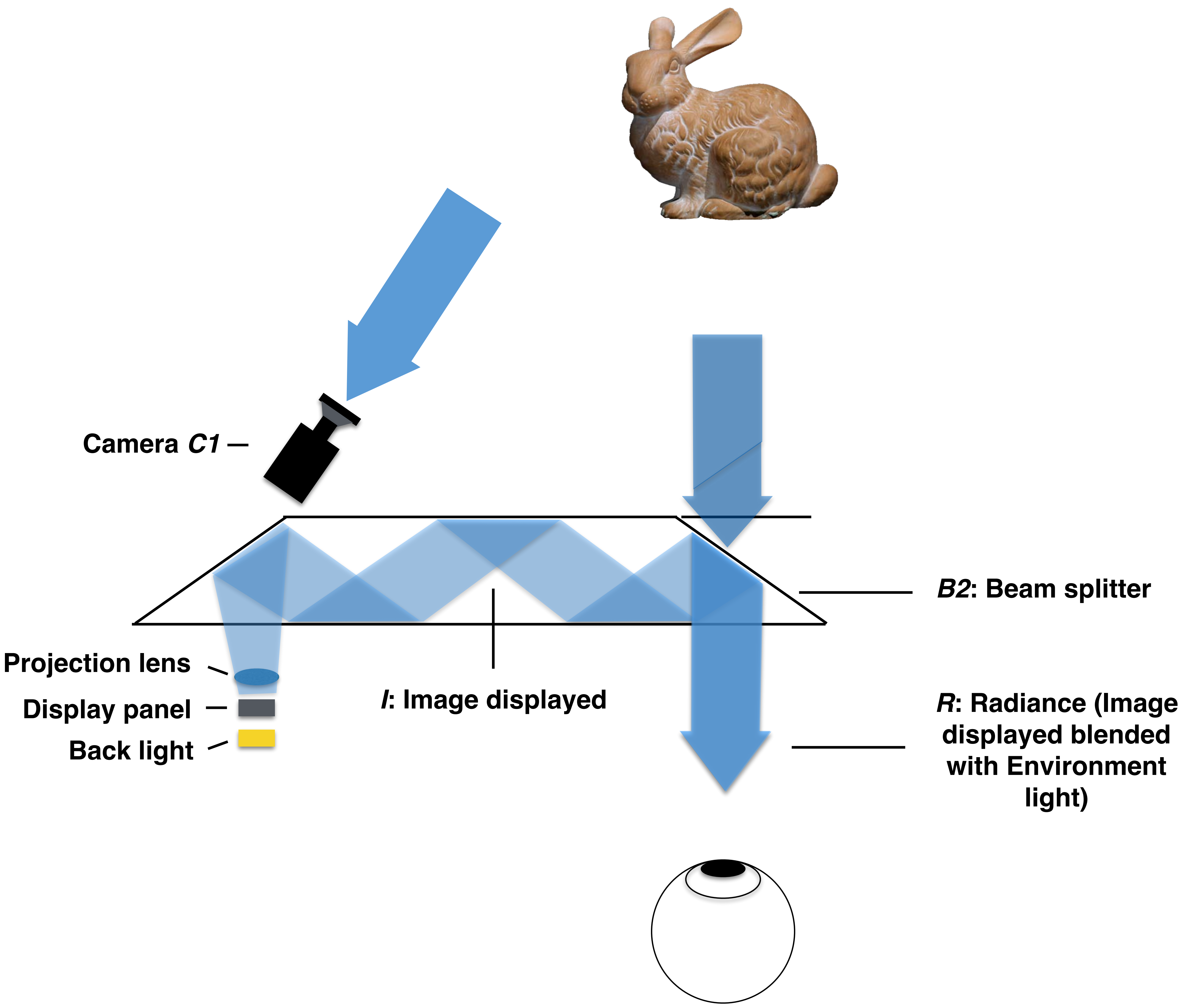
Image
Blending
Optical combiner



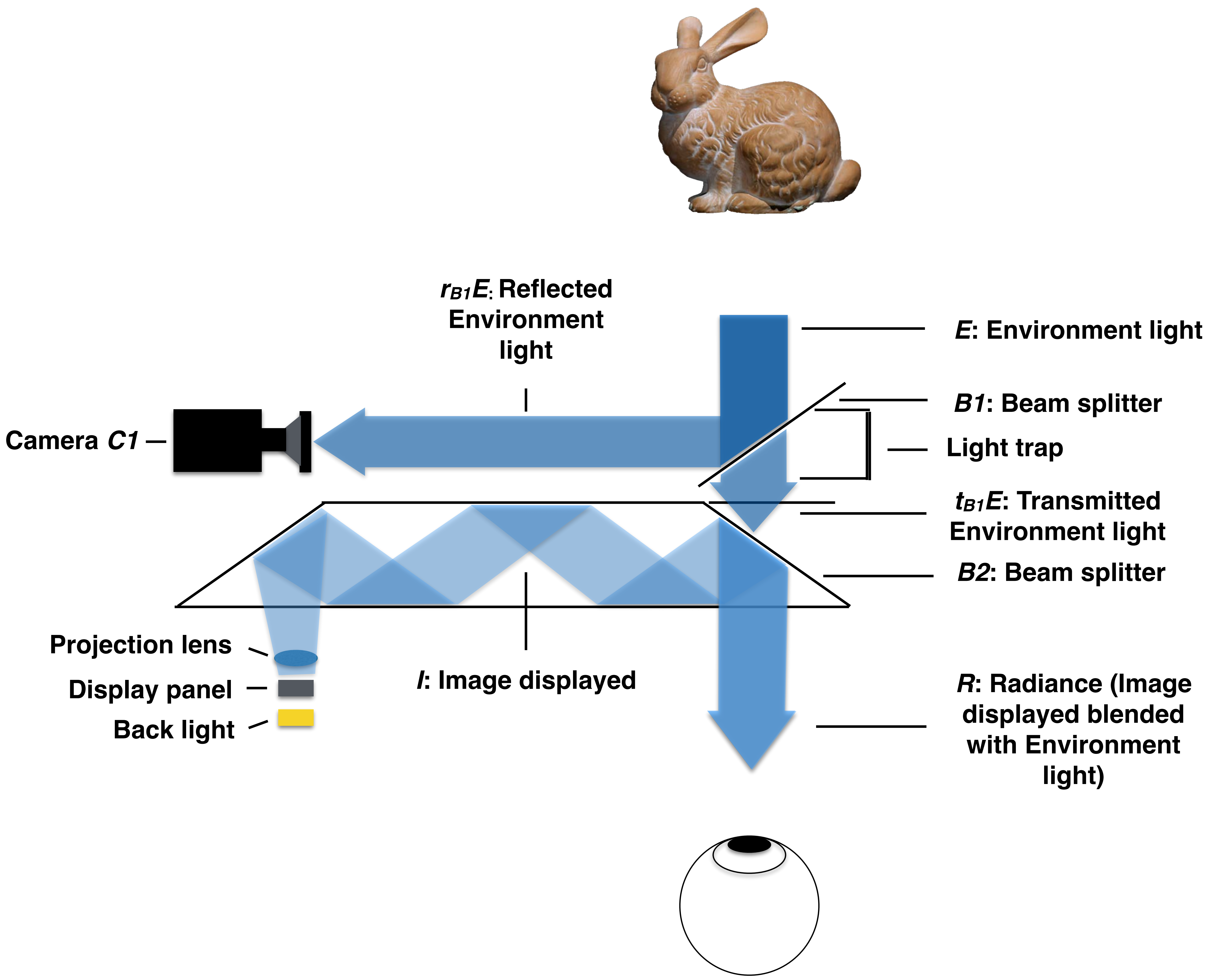
$$R = EM + IFM$$

$$I = \frac{(R - EM)}{FM}$$

Bimber et al. “Embedded entertainment with smart projectors” [12]



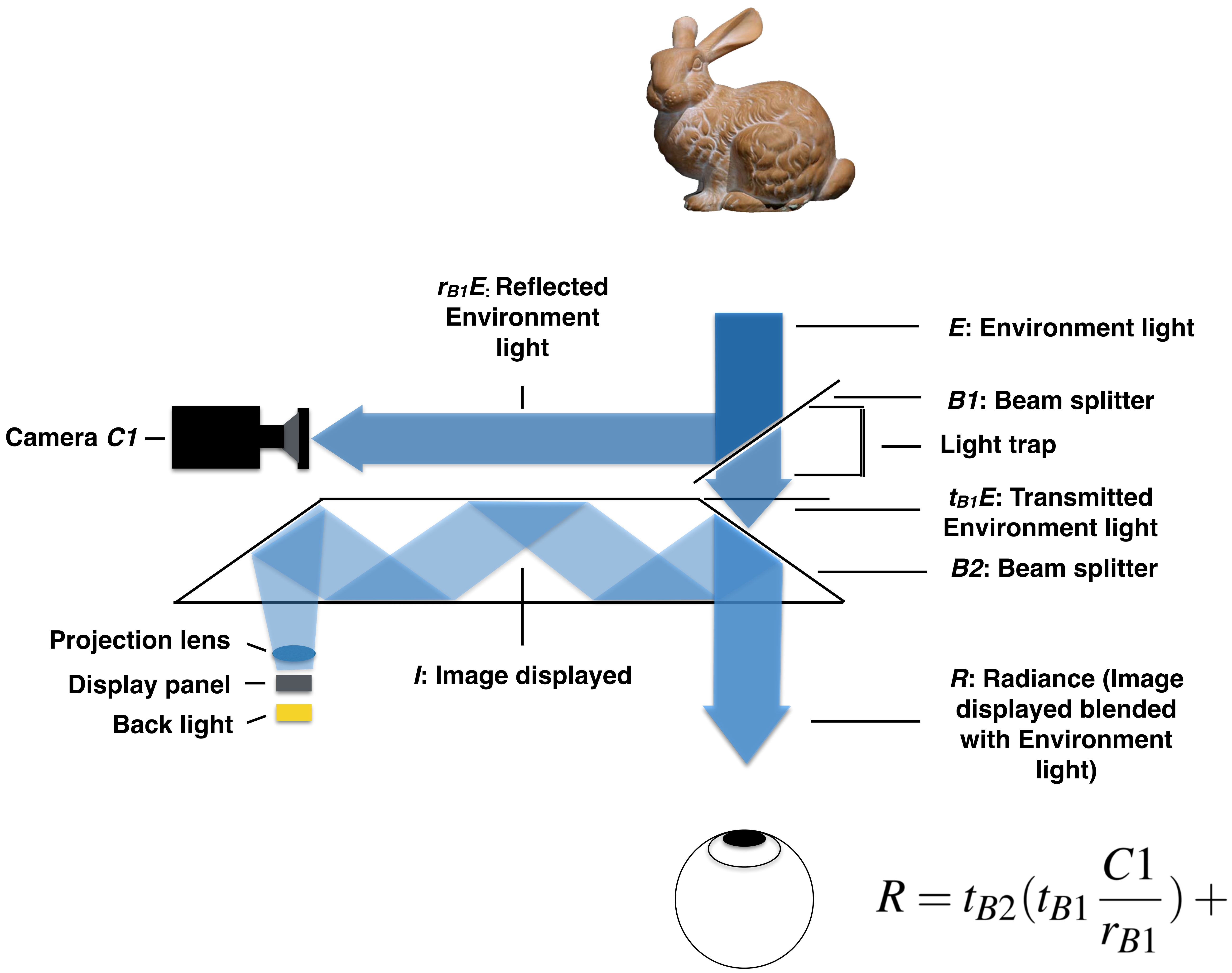
Langlotz et al. "Real-Time Radiometric Compensation for Optical See-Through Head-Mounted Displays" [89]



Langlotz et al. “Real-Time Radiometric Compensation for Optical See-Through Head-Mounted Displays” [89]

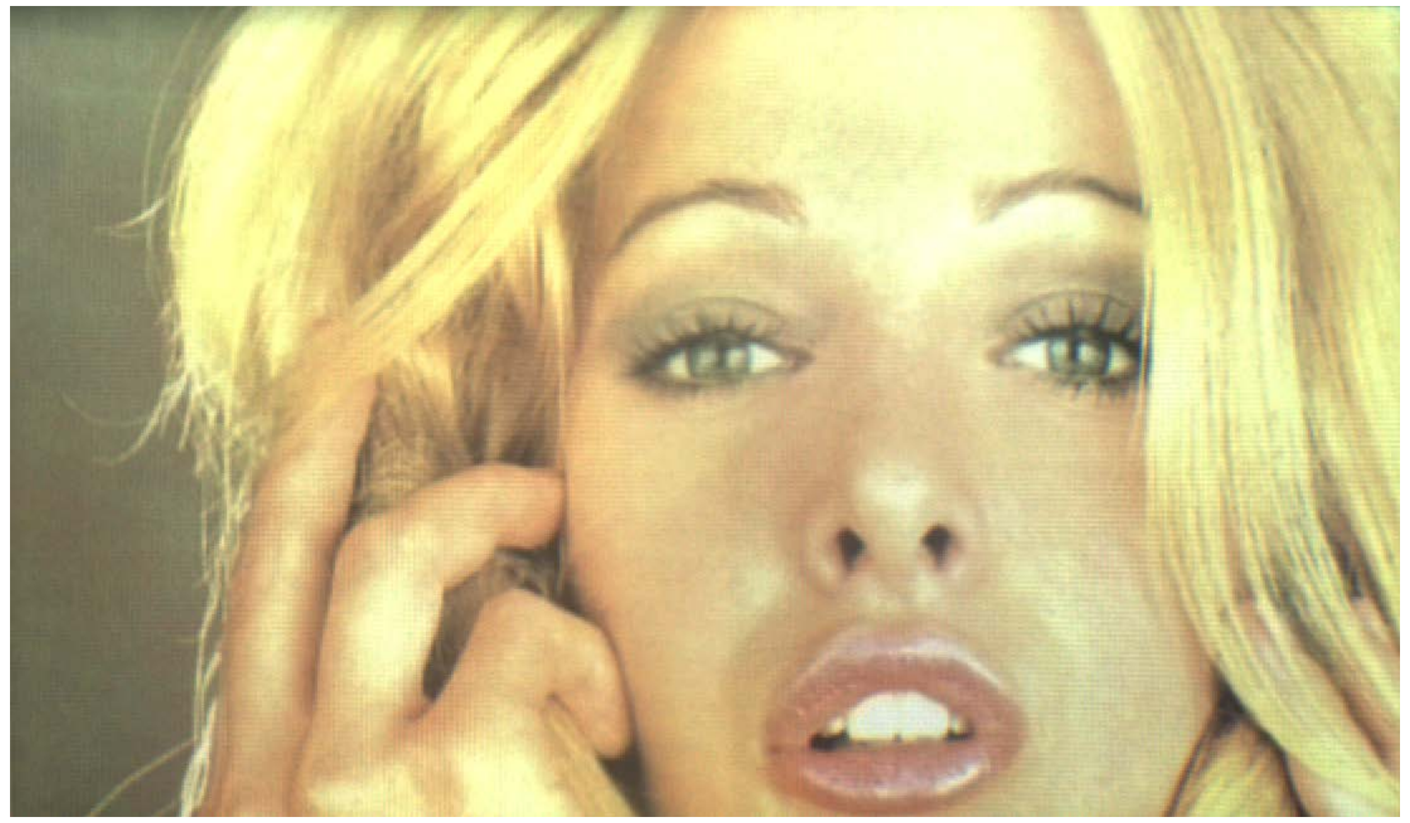
$$C1 = r_{B1}E$$

$$E = \frac{C1}{r_{B1}}$$

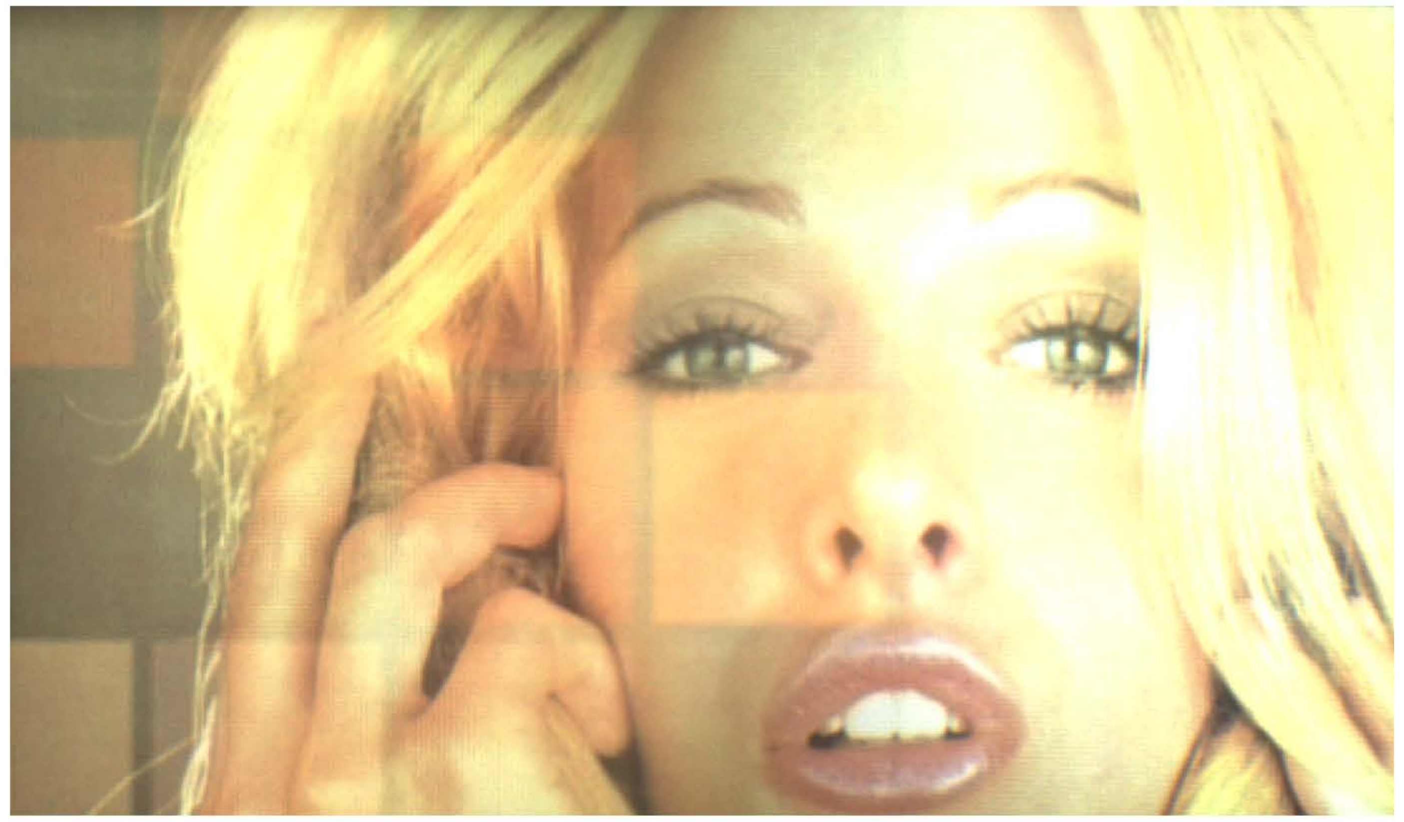


$$R = t_{B2}(t_{B1}\frac{C1}{r_{B1}}) + IFr_{B2}$$

Langlotz et al. "Real-Time Radiometric Compensation for Optical See-Through Head-Mounted Displays" [89]

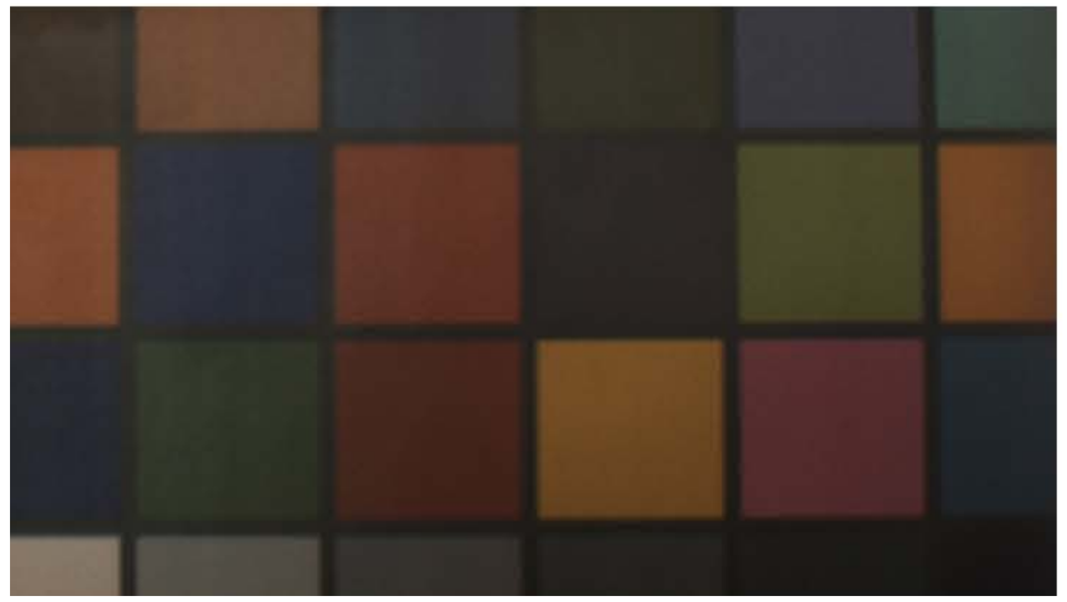


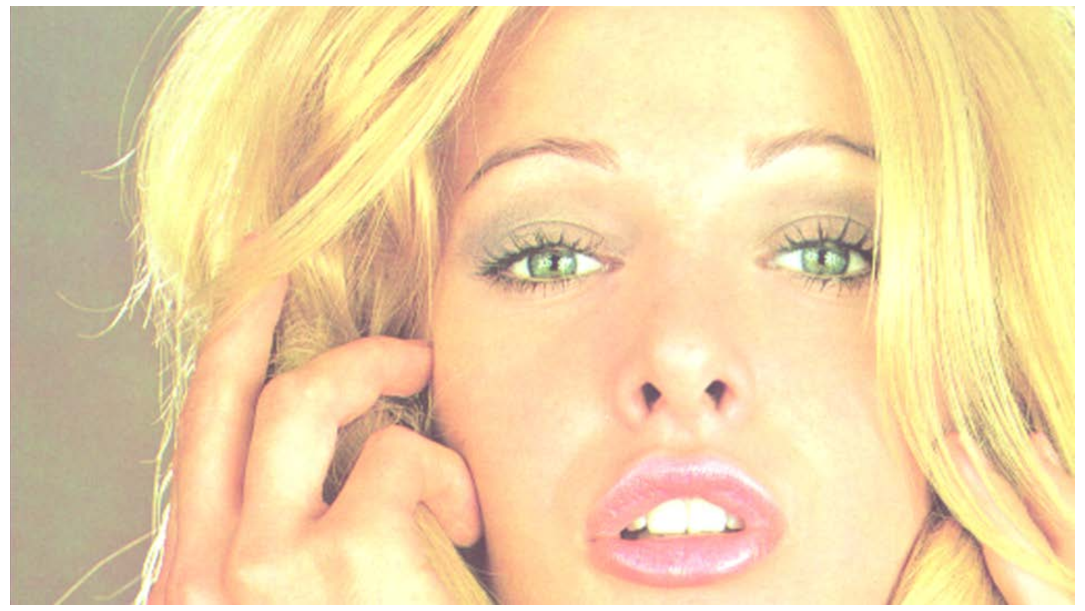
Reference



Uncorrected Optical See-through HMD

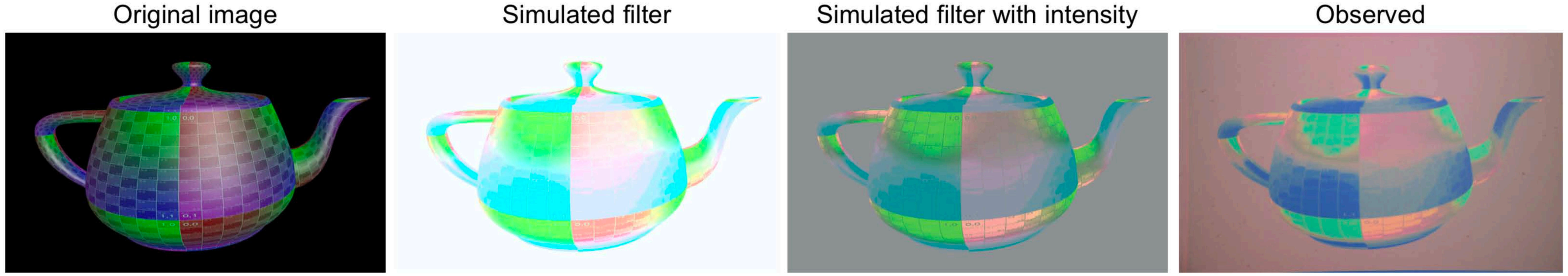
Corrected Optical See-through HMD





$$I = \frac{R - t_{B2}(t_{B1}\frac{C1}{r_{B1}})}{F r_{B2}}$$

Langlotz et al. “Real-Time Radiometric Compensation for Optical See-Through Head-Mounted Displays” [89]



Itoh et al. “Light Attenuation Display: Subtractive See-Through Near-Eye Display via Spatial Color Filtering” [57]

	Goal	Method	Software/Hardware	User Study	Portable Prototype
Itoh et al. [52]	Color reproduction	parametrized color response model	software	no	no
Sridharan et al. [144]	Color blending	color transmission database	software	no	no
Hincapié-Ramos et al. [26]	Color blending	color transmission database	software	no	no
Fukiage et al. [34]	Color blending	content visibility model	software	no	simulation
Weiland et al. [154]	Color blending	user adaptation modeling	software	no	no
Langlotz et al. [89]	Color blending	radiometric compensation	software	yes	yes
Wetzstein et al. [155]	View Modification	light filtering via SLM	hardware	yes	yes
Itoh et al. [57]	View Modification	light filtering via SLM	hardware	no	no
Mori et al. [112]	Brightness adjustment	adjustable liquid crystal shutter	hardware	yes	yes
Xu and Hua [160]	HDR imaging	two SLMs	hardware	no	no
Zhao et al. [163]	HDR imaging	two SLMs	hardware	no	no
Lincoln et al. [98]	HDR imaging	high speed LED with custom high speed controllers	hardware	no	no
Itoh et al. [59]	HDR imaging	HDR projector with dihedral corner reflection array	hardware	no	no

Visual Realism:
High Dynamic Range

	Goal	Method	Software/Hardware	User Study	Portable Prototype
Itoh et al. [52]	Color reproduction	parametrized color response model	software	no	no
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Hincapié-Ramos et al. [26]	Color blending	color transmission database	software	no	no
Fukiage et al. [34]	Color blending	content visibility model	software	no	simulation
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Visual Realism:
Accomodation Capability

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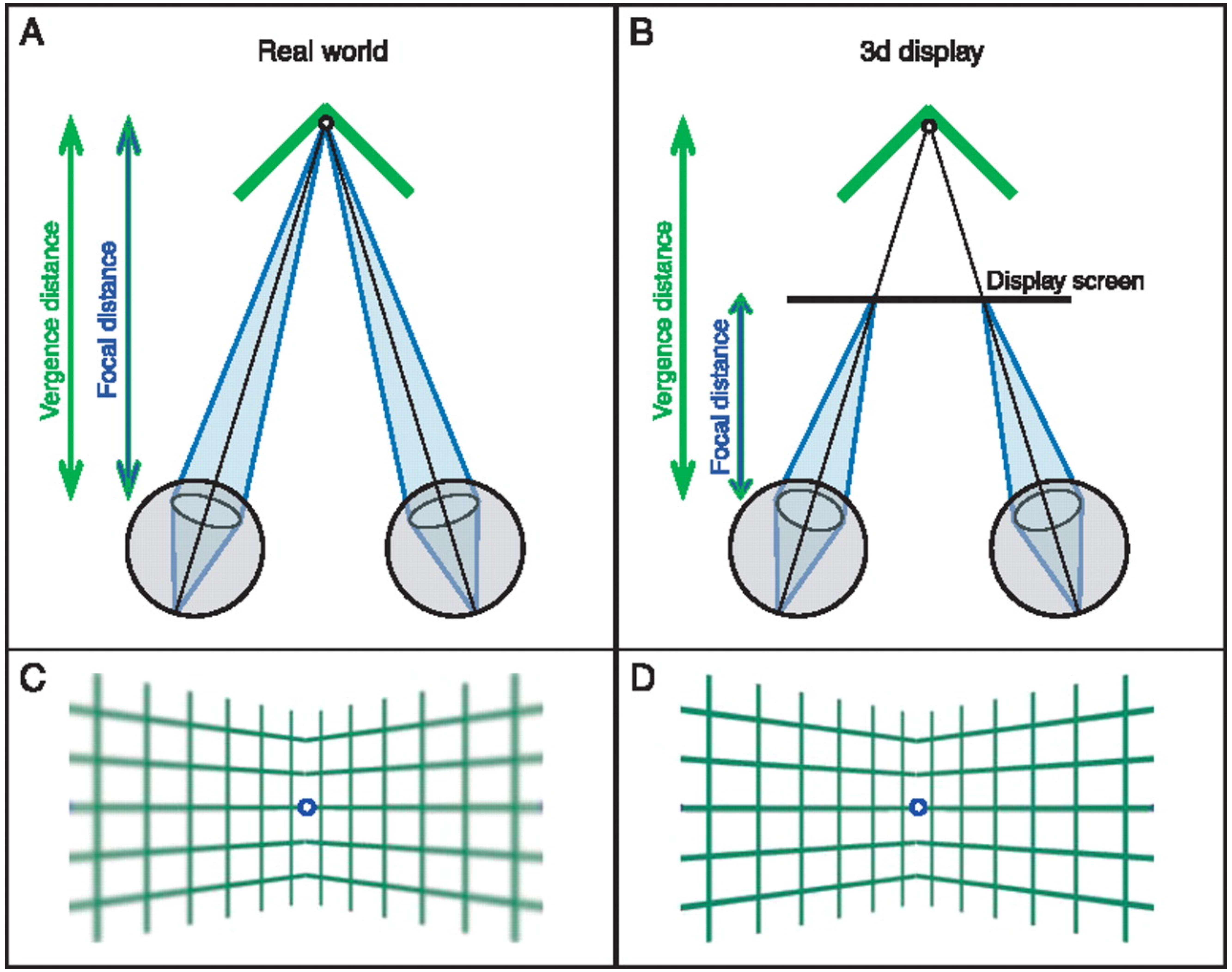
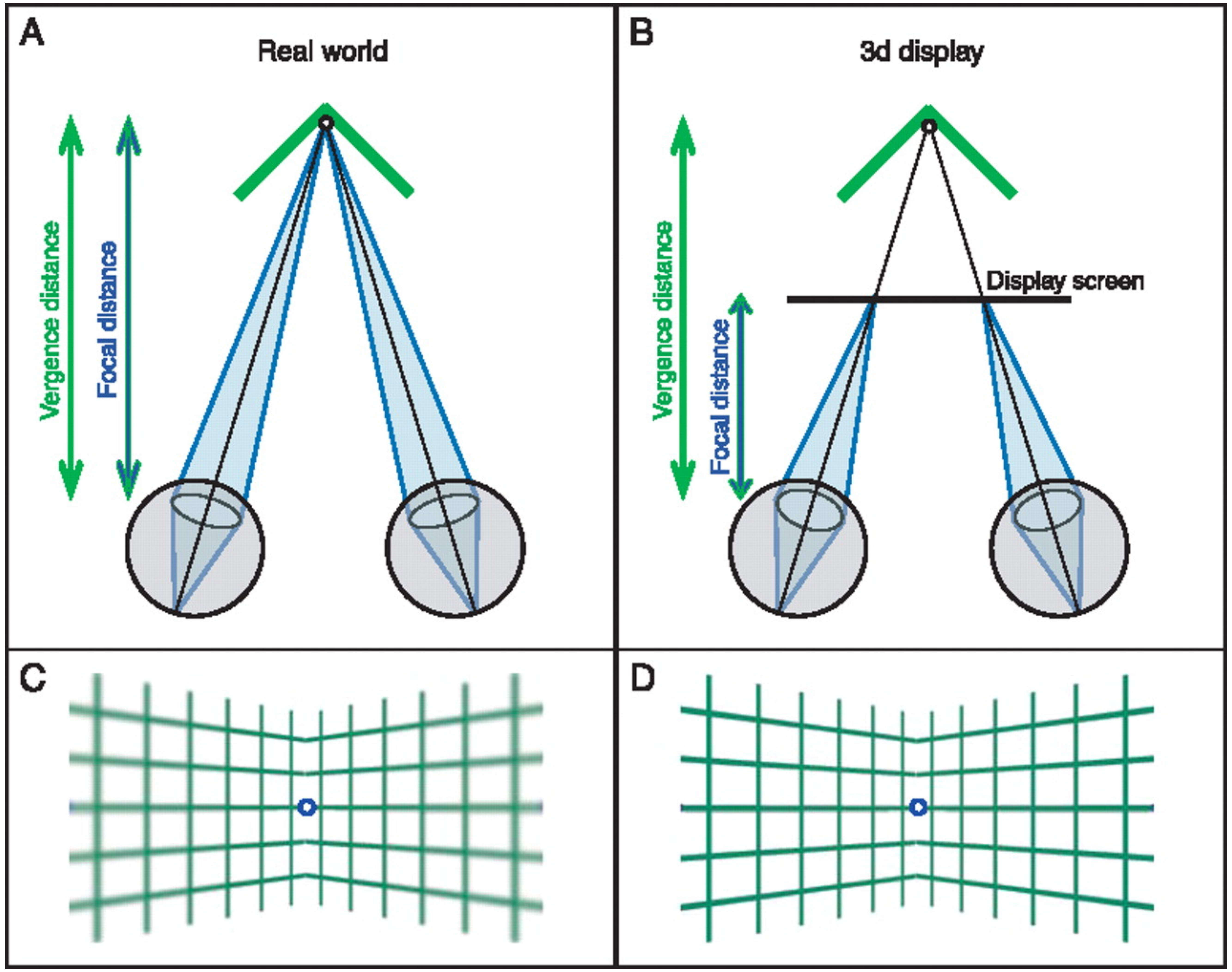
Vergence - Accomodation Conflict



Hoffmann et al. “Vergence–accommodation conflicts hinder visual performance and cause visual fatigue” [46]

Vergence - Accomodation Conflict



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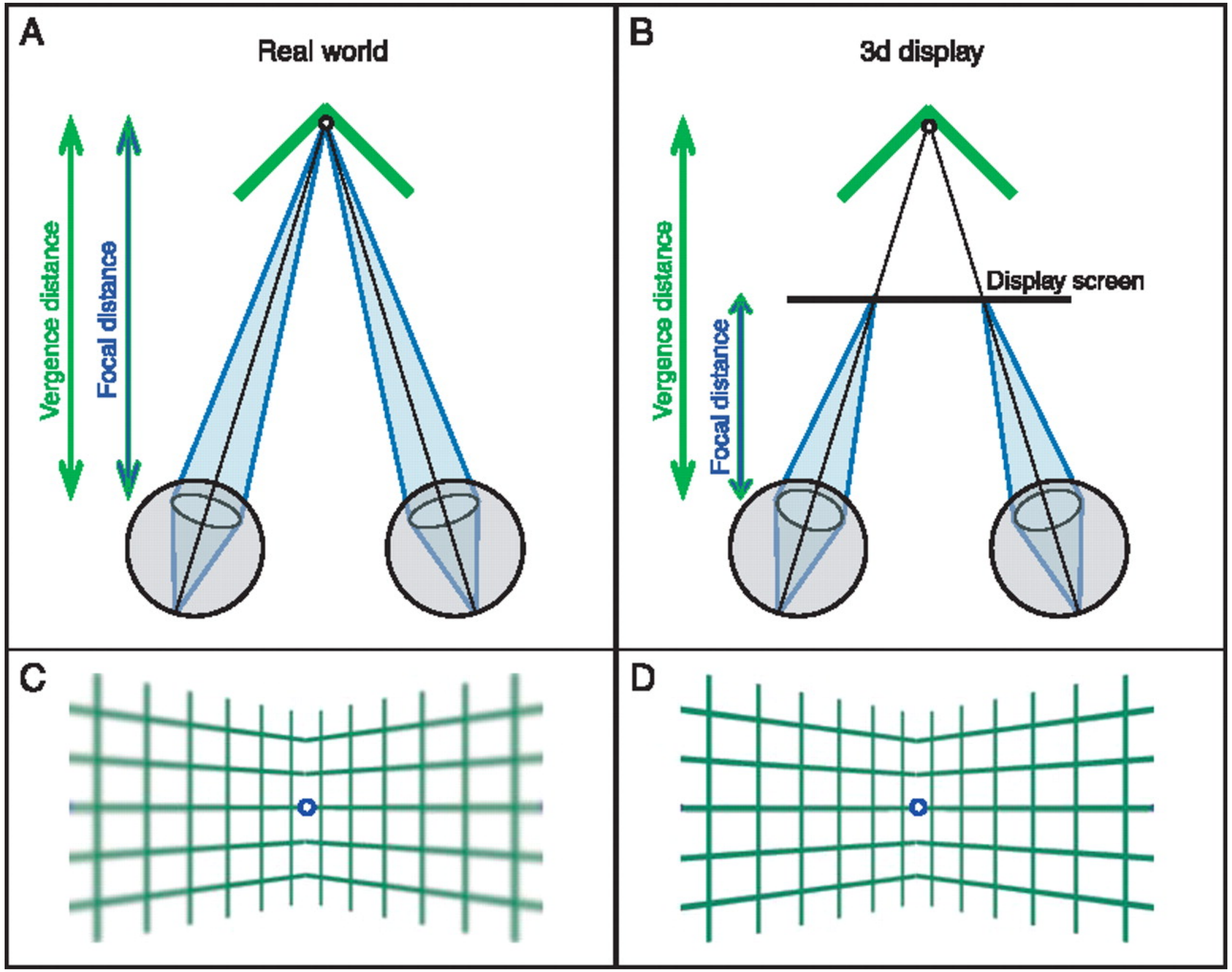
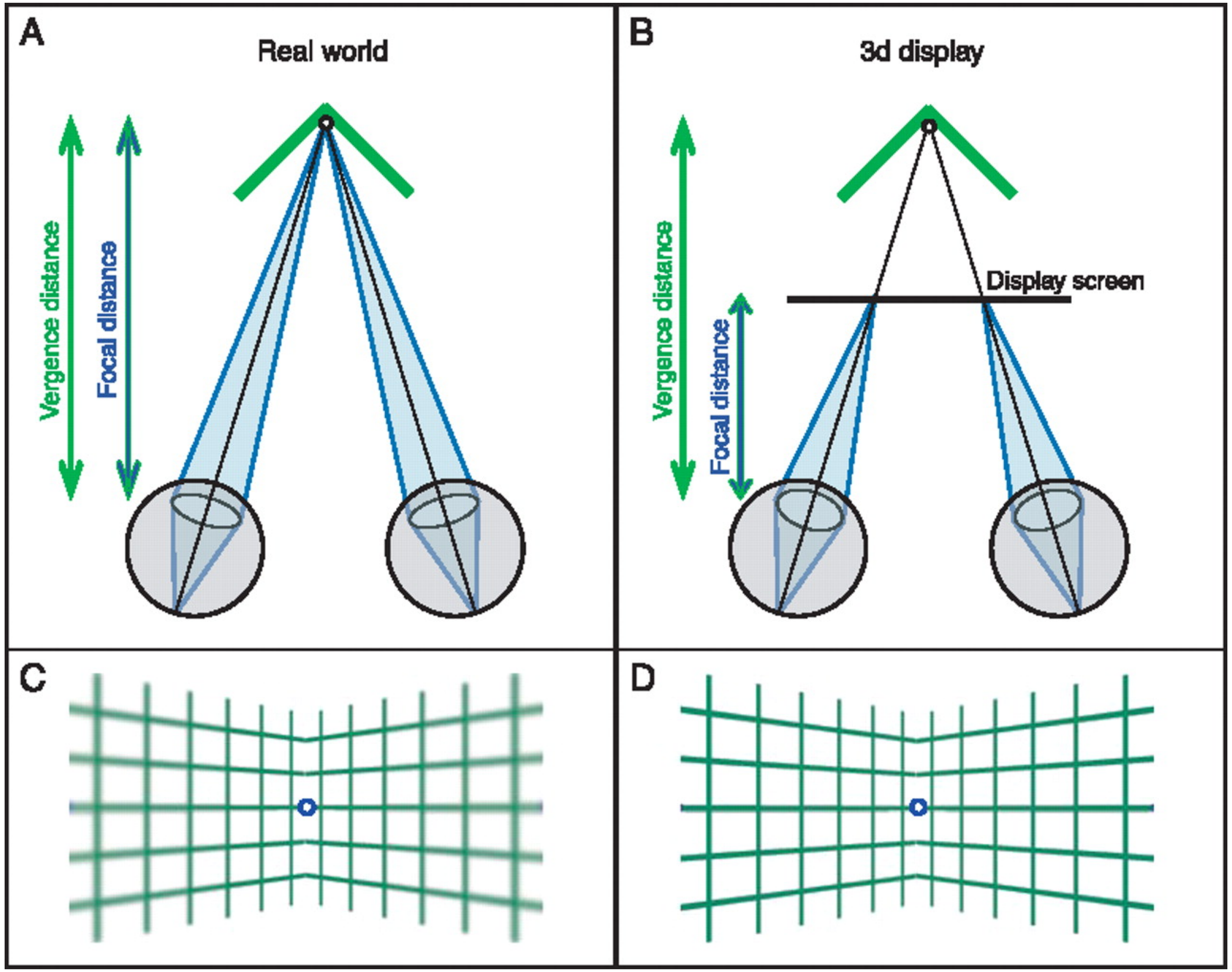
Vergence - Accomodation Conflict



Hoffmann et al. “Vergence–accommodation conflicts hinder visual performance and cause visual fatigue” [46]

Vergence - Accomodation Conflict



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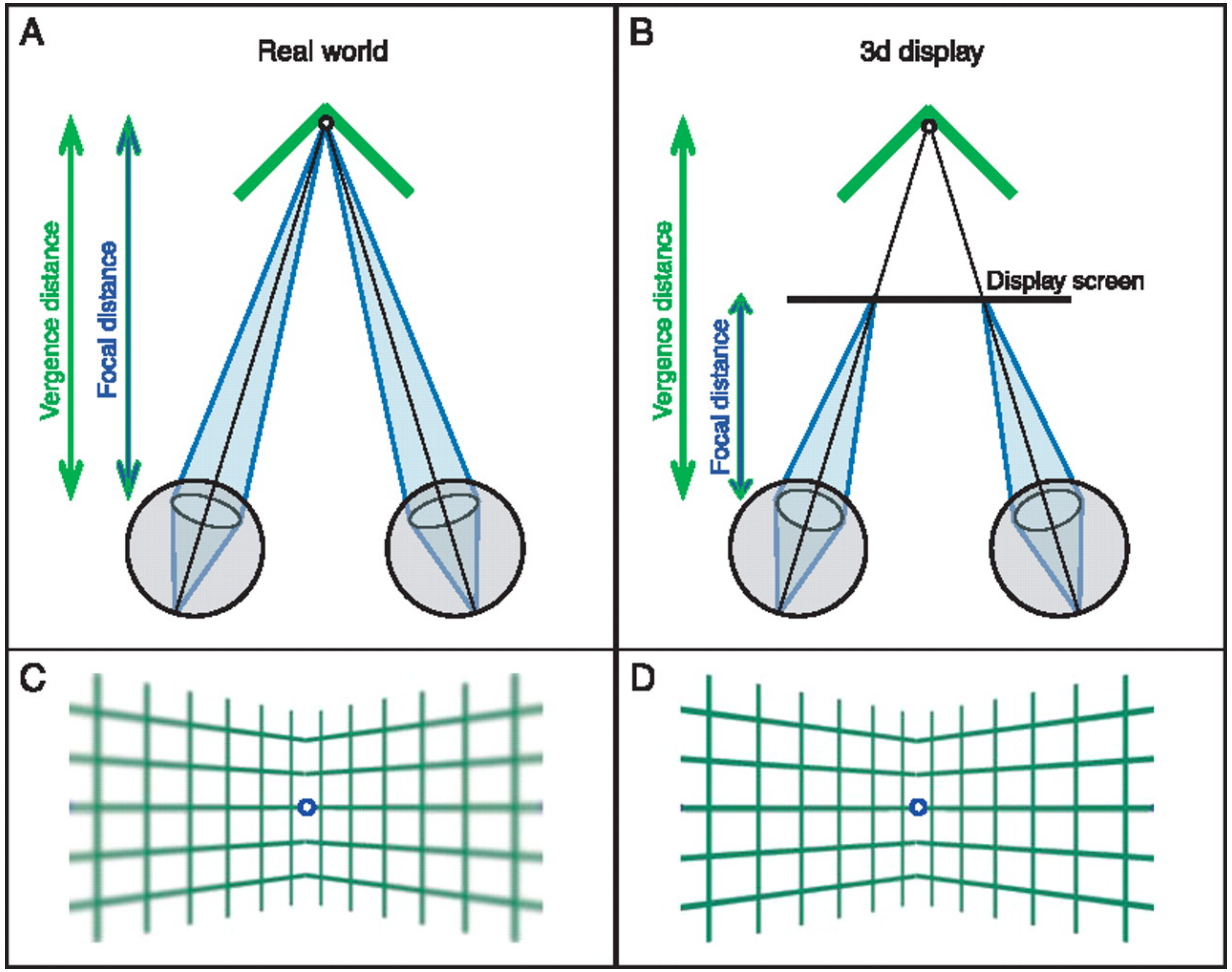
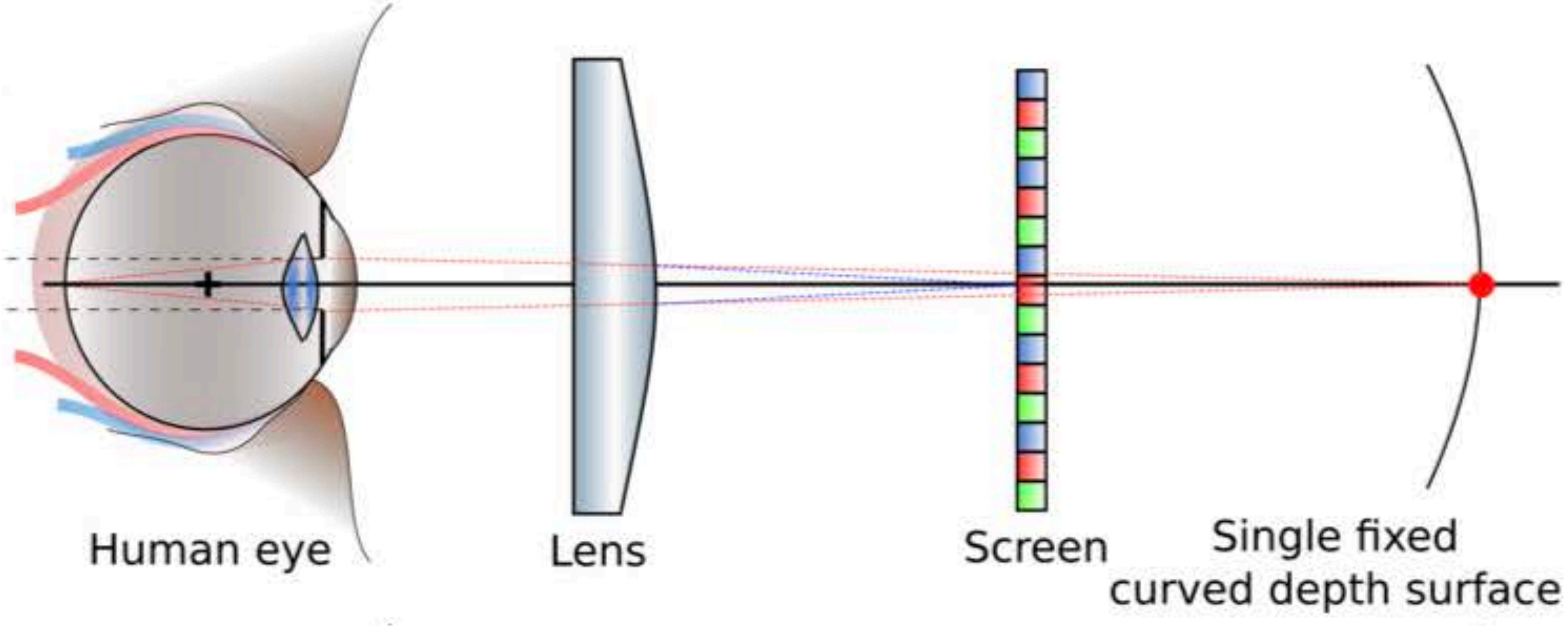
Vergence - Accomodation Conflict

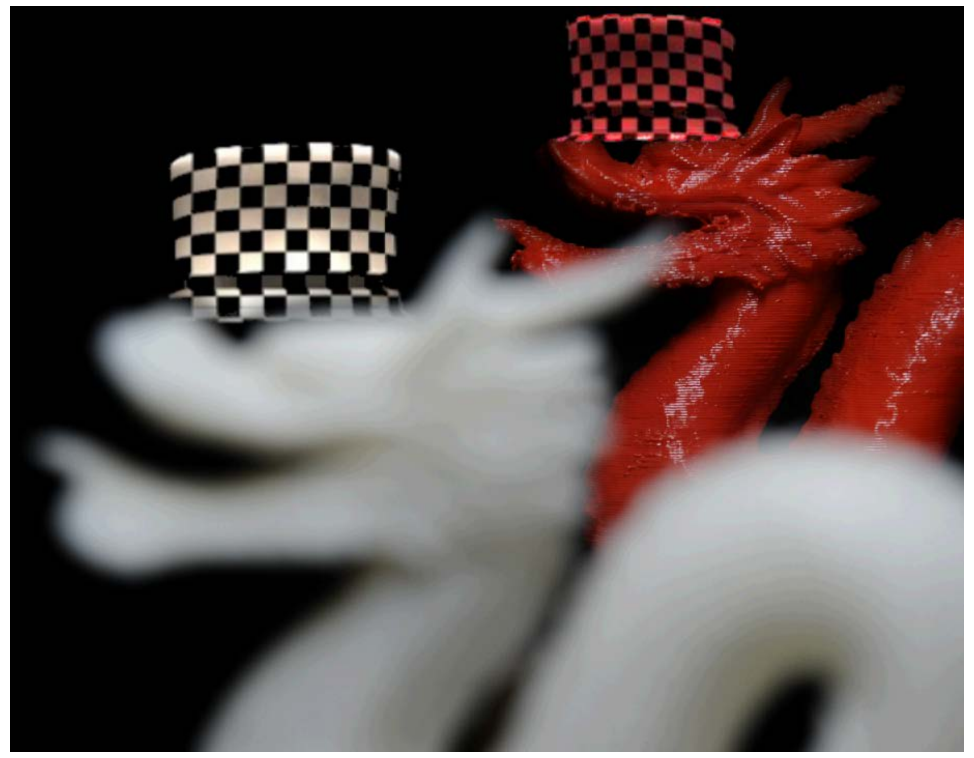


Hoffmann et al. “Vergence–accommodation conflicts hinder visual performance and cause visual fatigue” [46]

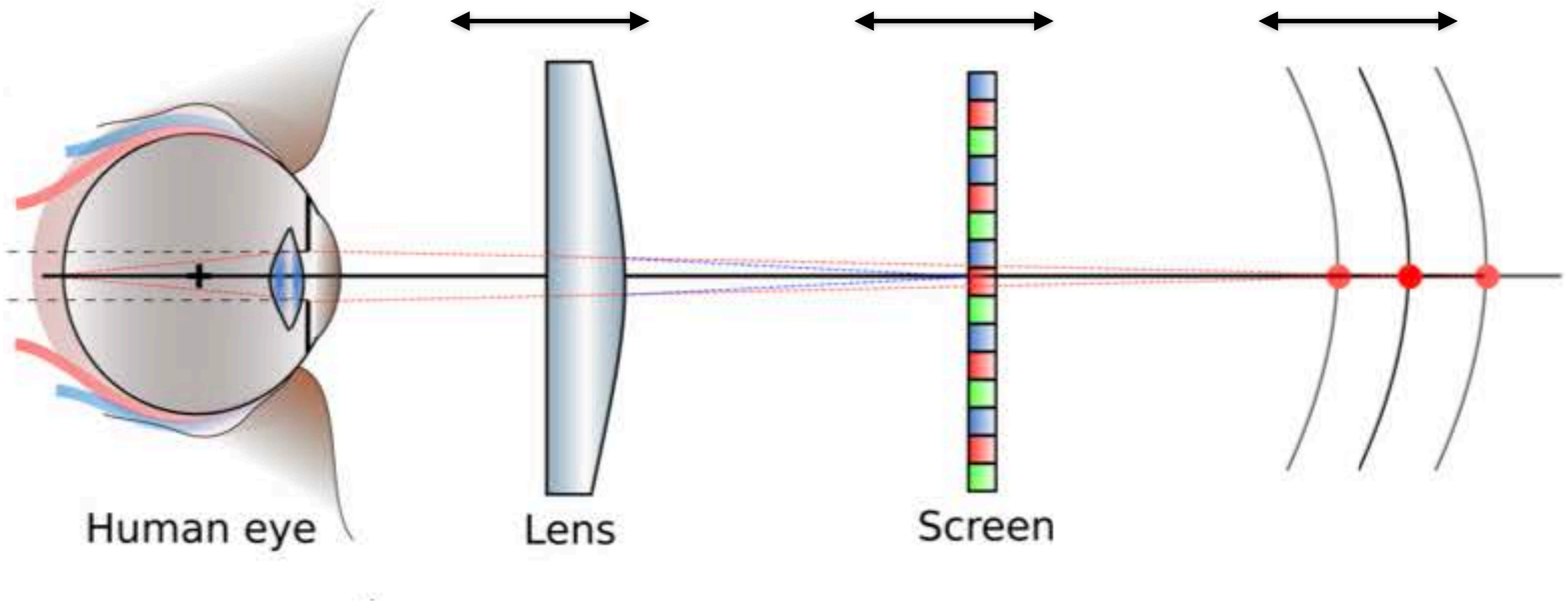
Fixed focus OST-HMDs



Koulieris et al. “Near-Eye Display and Tracking Technologies for Virtual and Augmented Reality” [46]

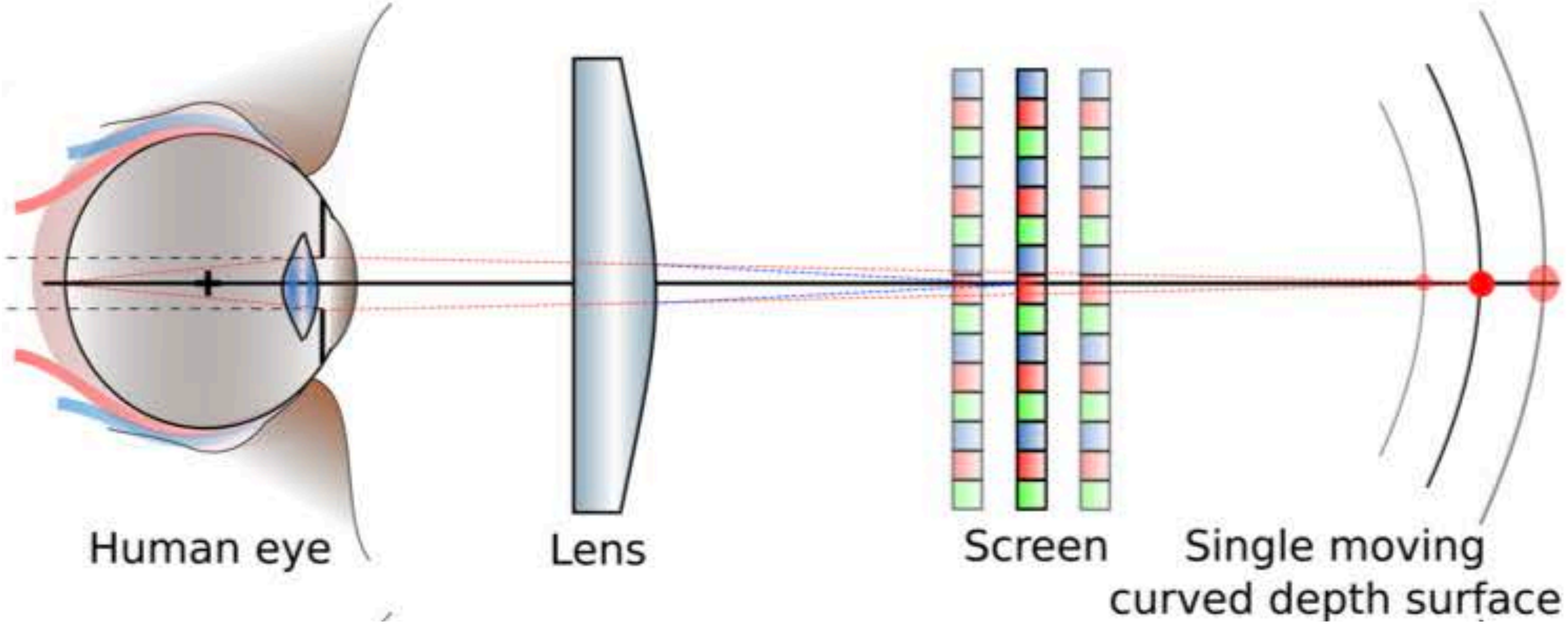


Adjustable Focus OST-HMDs



Adapted from Koulieris et al. “Near-Eye Display and Tracking Technologies for Virtual and Augmented Reality” [46]

Varifocal OST-HMDs



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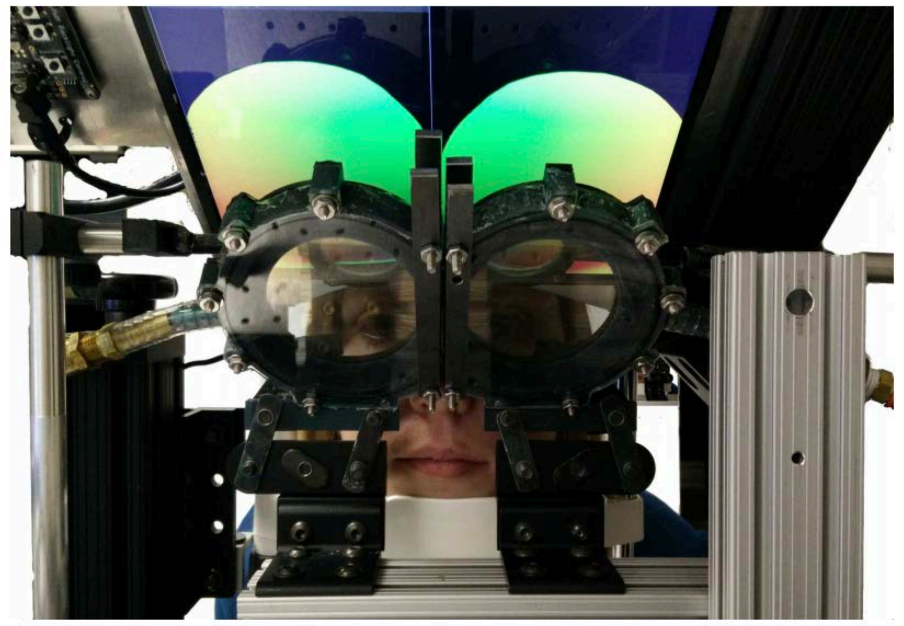
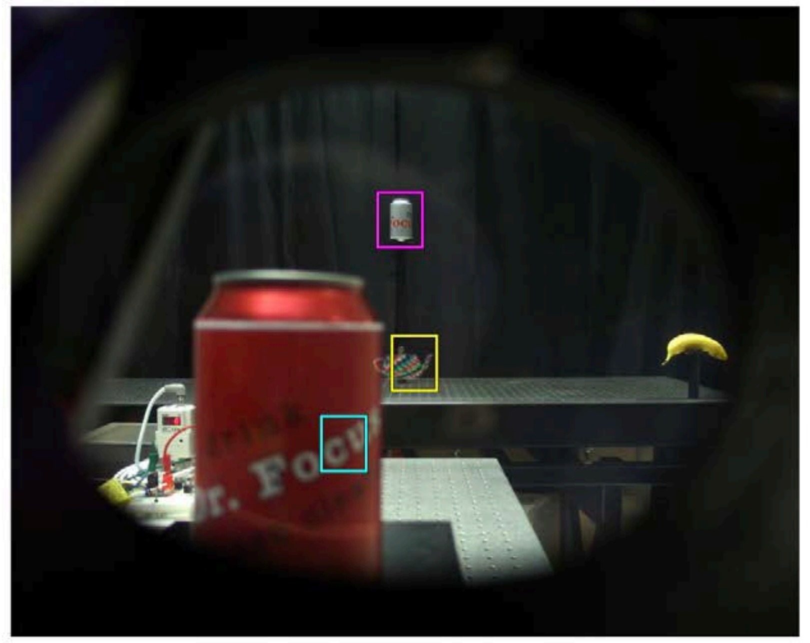


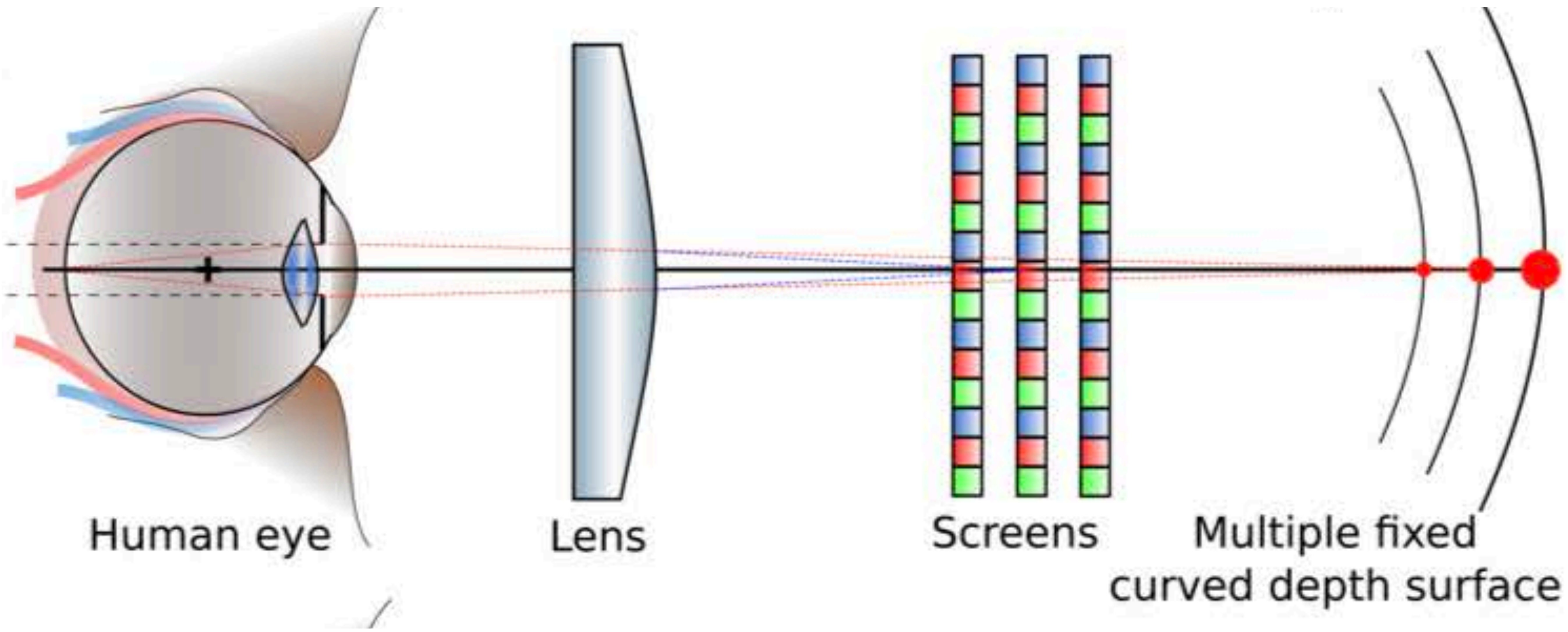
Near focus



Far focus

Dunn et al. “Wide Field Of View Varifocal Near-Eye Display Using See-Through Deformable Membrane Mirrors” [30]

Multifocal OST-HMDs



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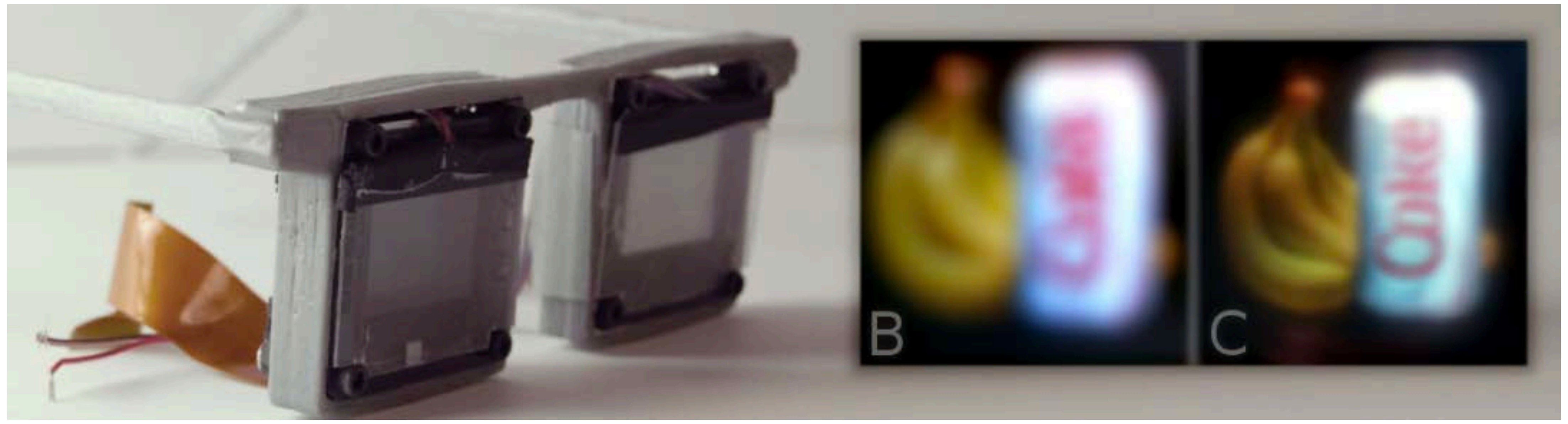
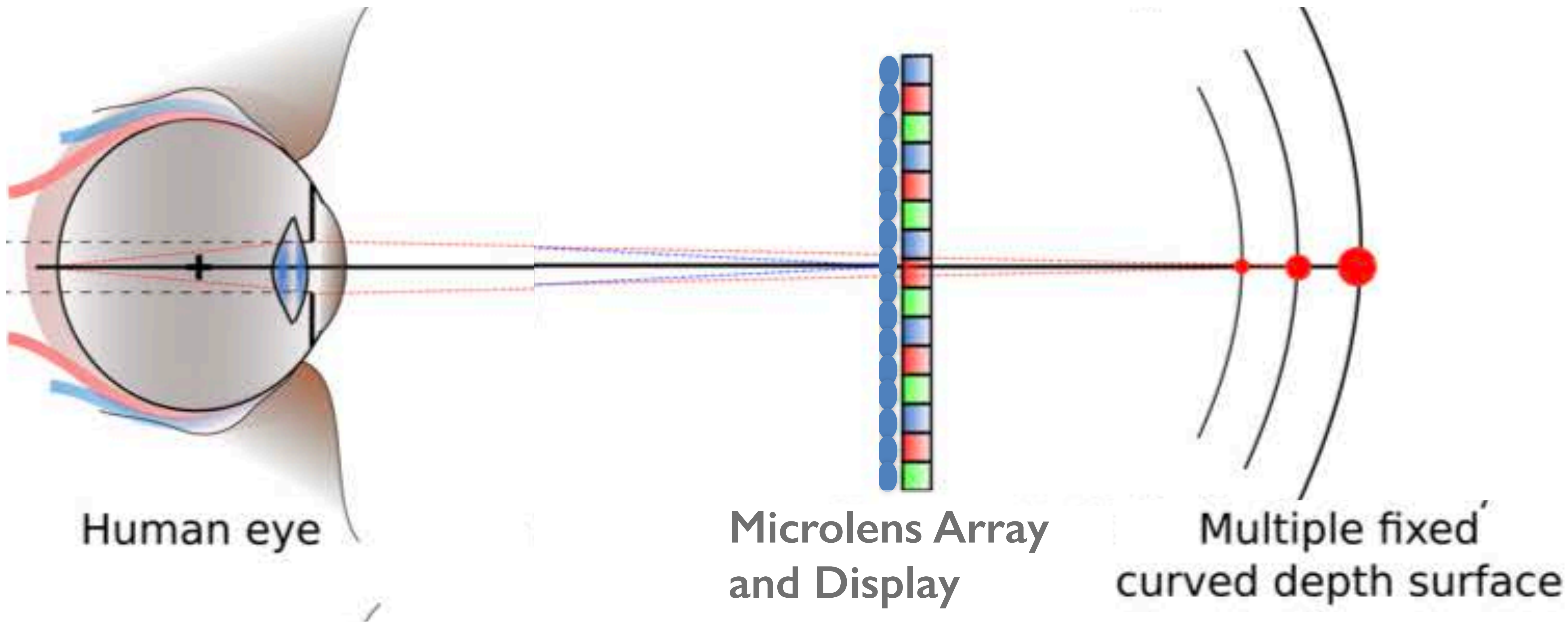


Maimone and Fuchs “Computational Augmented Reality Eyeglasses

Lightfield OST-HMDs



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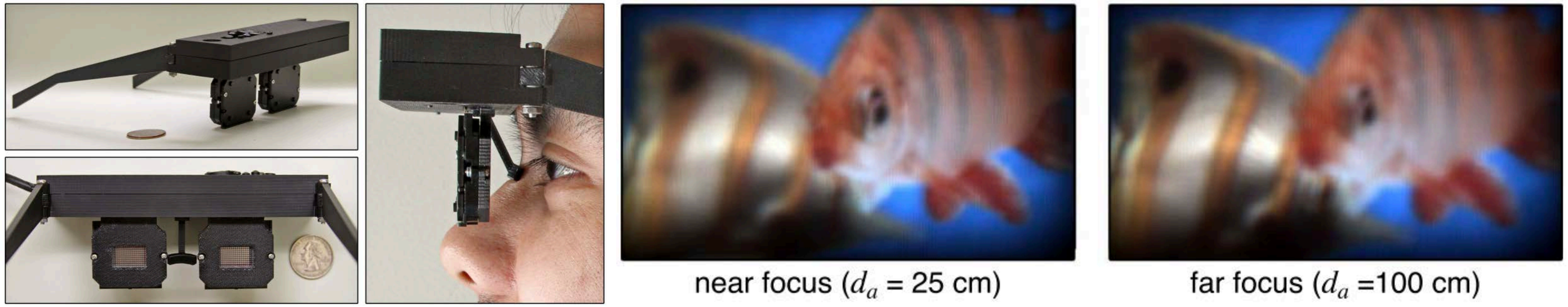
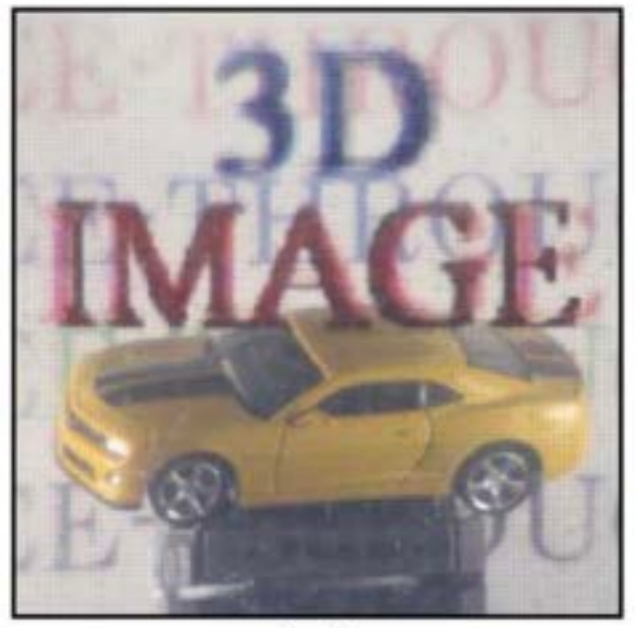
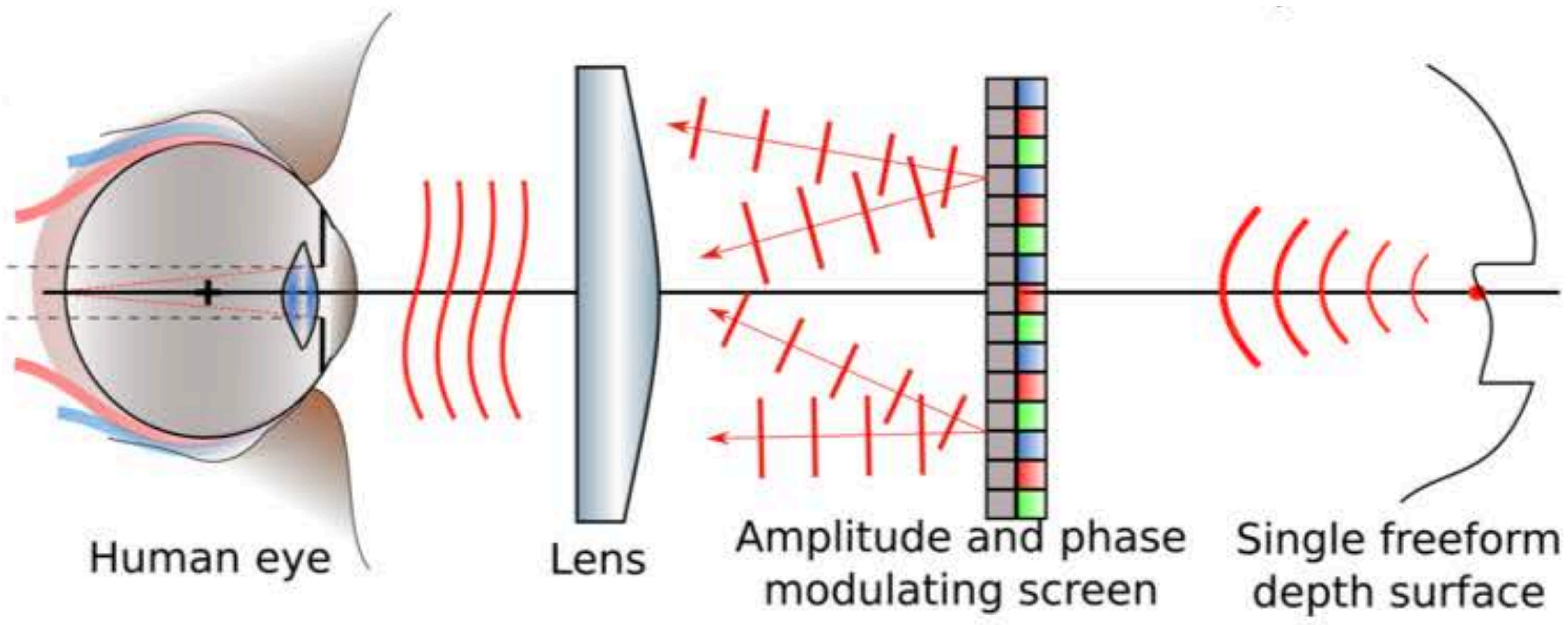


Lanman and Luebke [93]

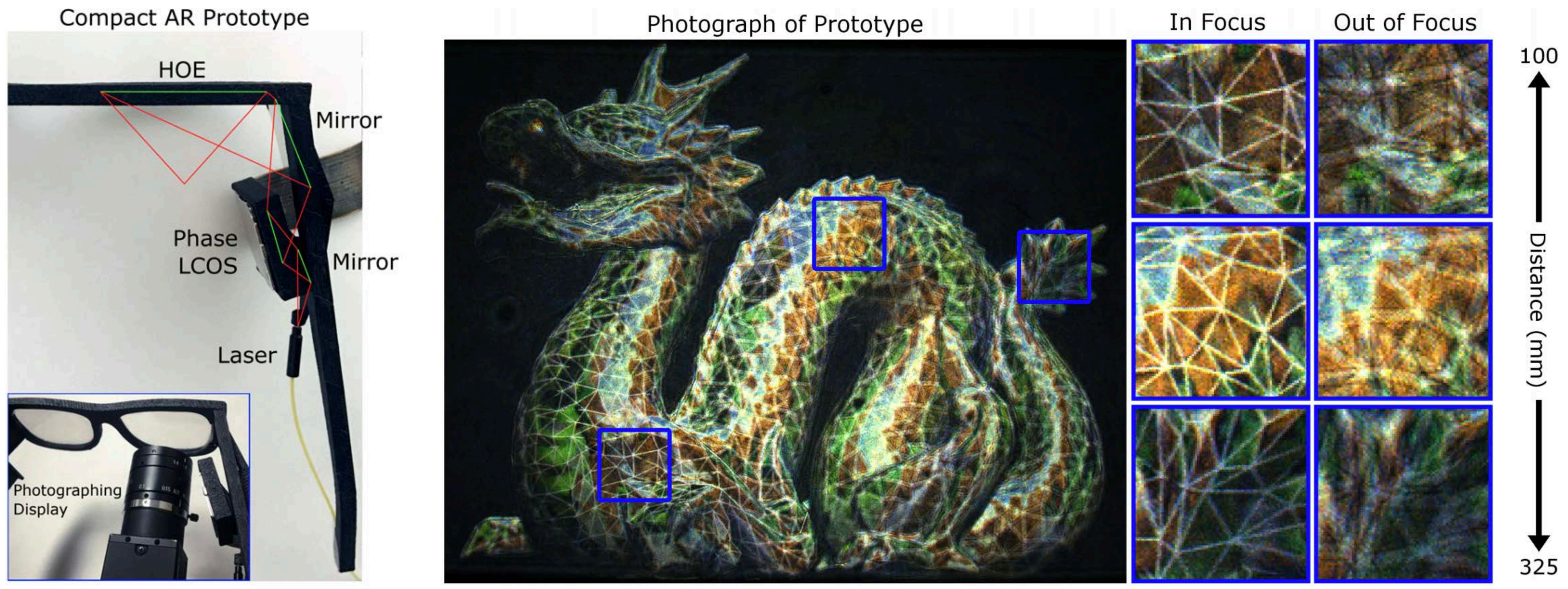


Yamaguchi and Takaki [161]

Holographic OST-HMDs



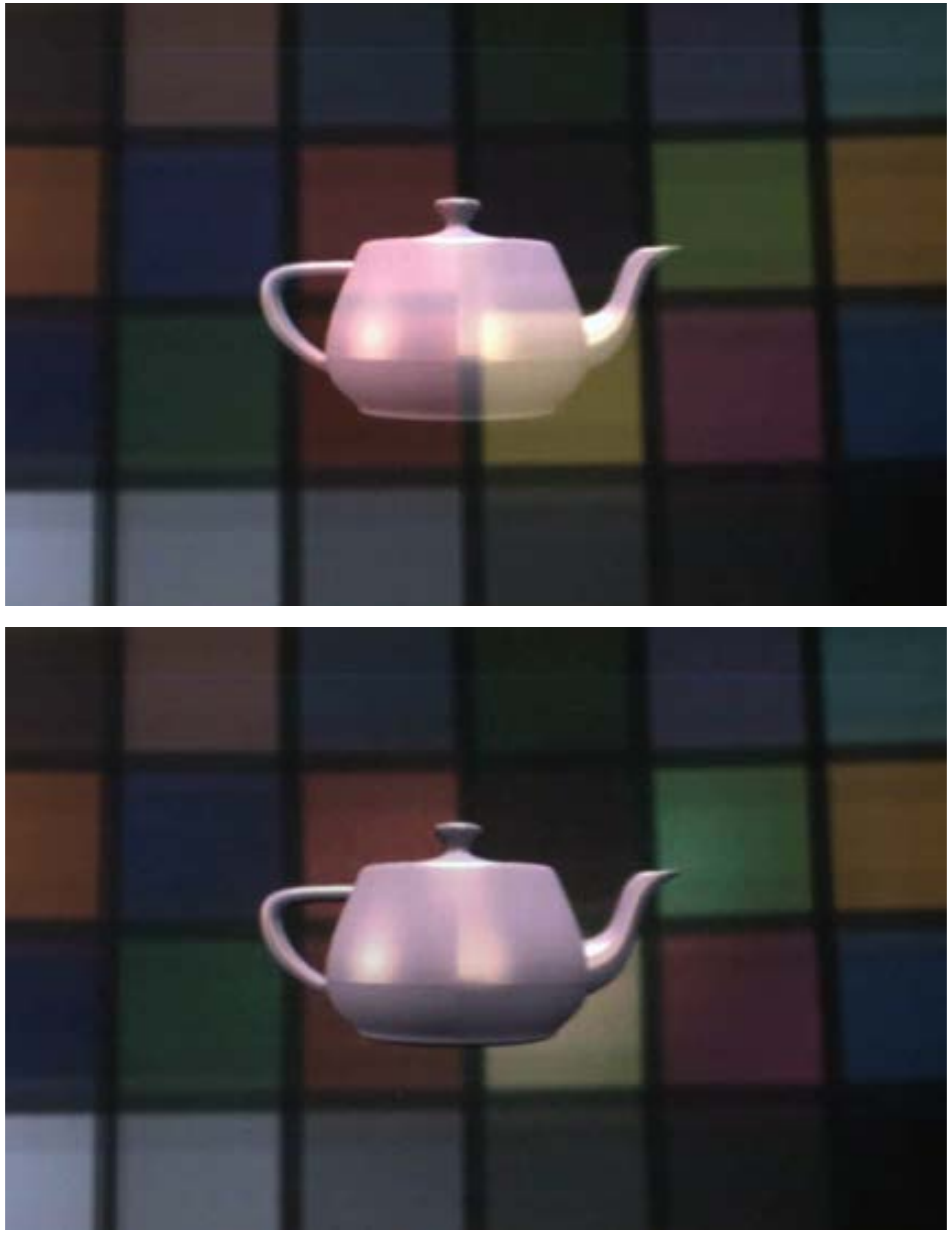
Koulieris et al. “Near-Eye Display and Tracking Technologies for Virtual and Augmented Reality” [46]



Maimone et al. “Holographic Near-Eye Displays for Virtual and Augmented Reality” [104]

	Mechanism	Classification	See-Through	Field of View	Resolution	Eye Tracking Needed	Optical Complexity	Form Factor	Computational Demand	Miniature Prototype
Lanman and Luebke [93]	microlenses	light-field	no	33.3°	low	yes	simple	thin	moderate	yes
Yamaguchi and Takaki [161]	microlenses	light-field	yes	4.3°	low	yes	simple	thin	moderate	no
Otao et al. [118]	microlenses	light-field	no	narrow	low	yes	simple	bulky	moderate	yes
Maimone et al. [105]	pinlight display	always-in-focus	yes	80°	low	recommended	simple	thin	moderate	yes
Akşit et al. [5]	pinhole display	always-in-focus	no	83°	low	recommended	simple	thin	moderate	yes
Song et al. [141]	pinhole display	always-in-focus	yes	narrow	low	recommended	simple	thin	moderate	yes
Jang et al. [61]	laser with steering mirror	holographic	yes	68°	moderate	yes	complex	thin	high	yes
Maimone et al. [104]	SLM	holographic	yes	80° horizontal	high	yes	complex	thin	moderate	yes
Shi et al. [140]	SLM	holographic	no	N/A	high	yes	complex	moderate	high	no
Moon et al. [111]	SLM	holographic	yes	narrow	N/A	yes	complex	moderate	high	yes
Huang et al. [50]	stacked LCD panels	multi-plane	no	125°	high	no	simple	bulky	high	yes
Lee et al. [95]	savart plate	multi-plane	yes	37°	high	no	moderate	moderate	low	yes
Yoo et al. [162]	polarized lenses	multi-plane	yes	7.5° horizontal	high	no	moderate	moderate	low	no
Liu et al. [102]	polymer stabilized scattering shutters	multi-plane	yes	narrow	N/A	no	simple	moderate	low	no
Maimone and Fuchs [103]	stacked LCD panels	multi-plane	yes	65°	low	no	simple	moderate	high	yes
Rolland et al. [132]	stacked planar displays	multi-plane	yes	N/A	high	no	simple	moderate	low	no
Liu et al. [101]	focus tunable lens	varifocal	yes	28°	moderate	no	complex	moderate	low	no
Rathinavel et al. [125]	focus tunable lens	varifocal	yes	15.3°	moderate	no	complex	bulky	low	no
Xia et al. [159]	focus tunable lens	varifocal	yes	37°	moderate	no	complex	bulky	low	no
Dunn et al. [29, 30]	focus tunable membrane	varifocal	yes	103°	moderate	yes	simple	bulky	moderate	yes
Wilson and Hua [158]	alvarez lens	varifocal	yes	103°	moderate	no	complex	moderate	moderate	no
Matsuda et al. [107]	SLM	focal surface	no	18°	high	yes	complex	bulky	high	yes

Visual Realism:
Occlusion Capability



Itoh et al. “Occlusion leak compensation for optical see-through displays using a single-layer transmissive spatial light modulator” [53]

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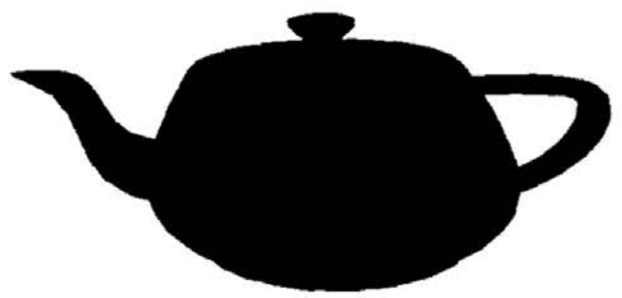
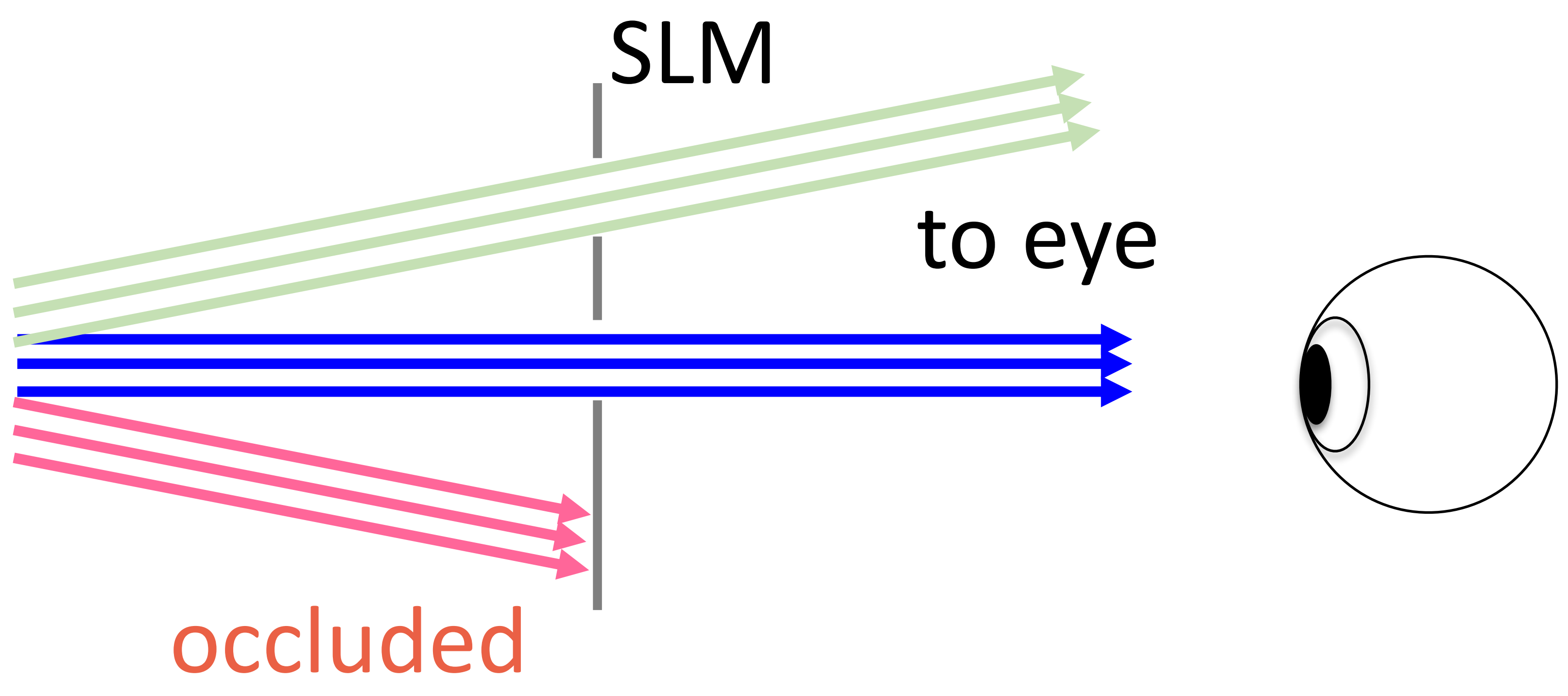
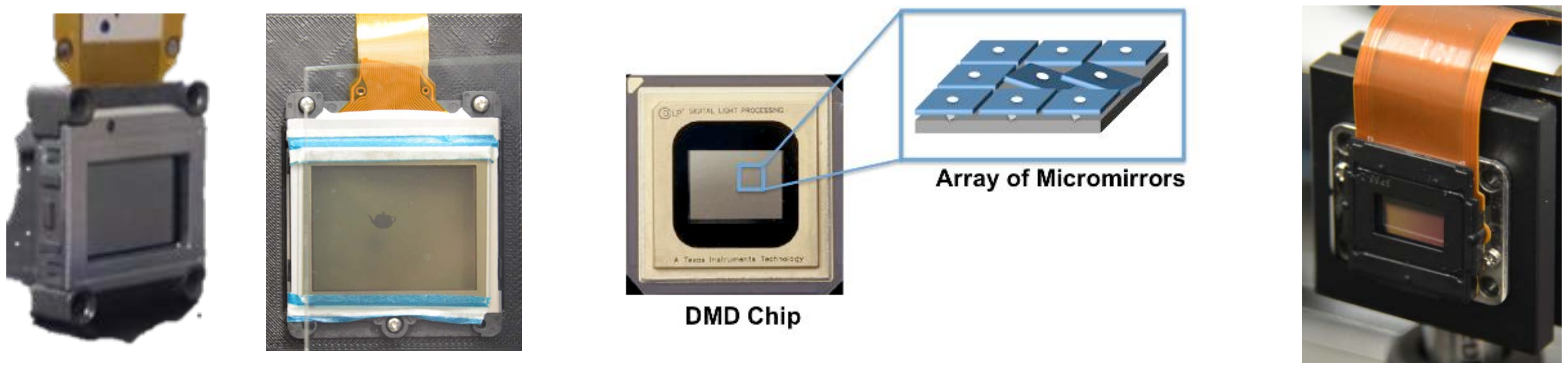
Direction Occlusions



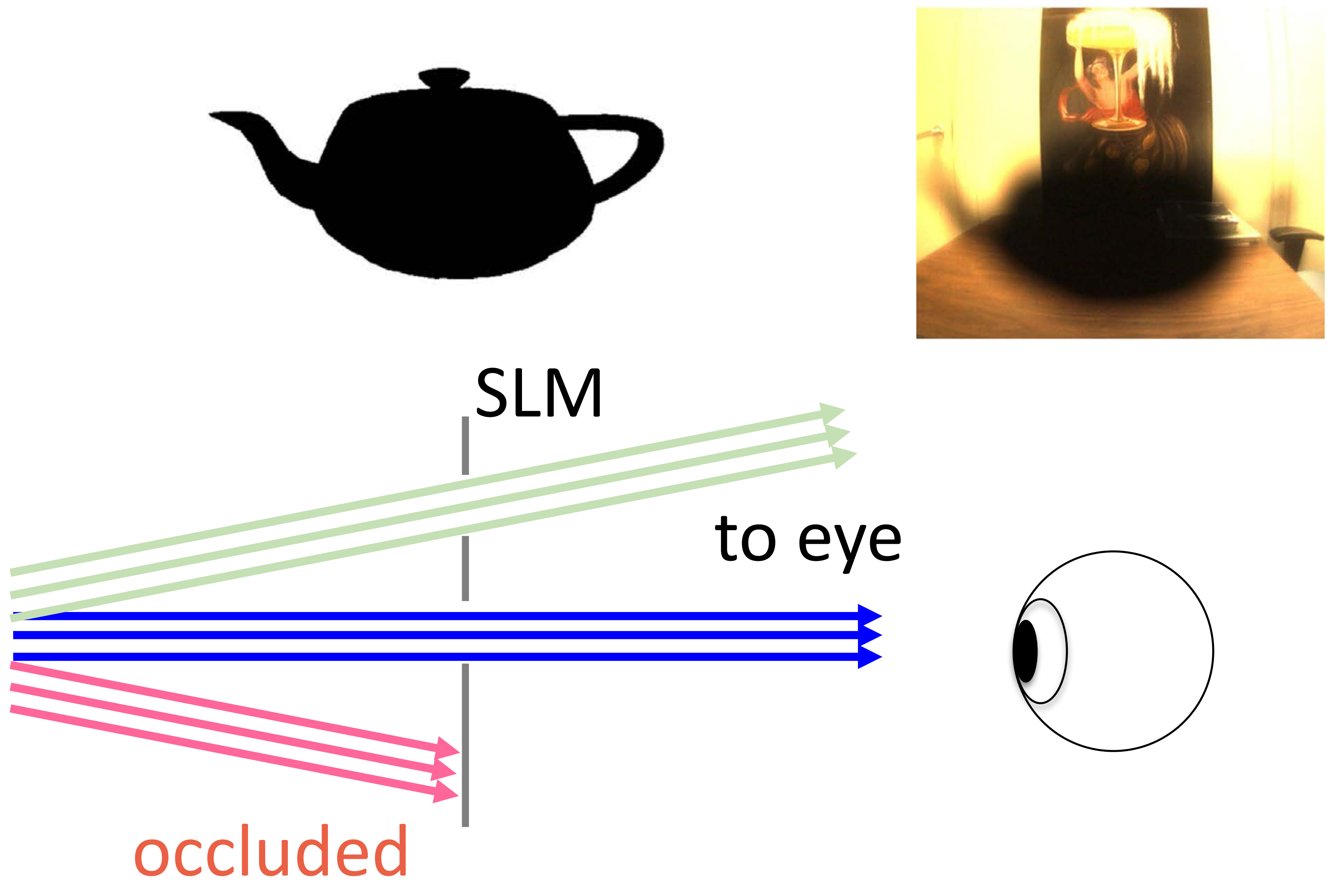


Examples for Spatial Light Modulators (SLMs)

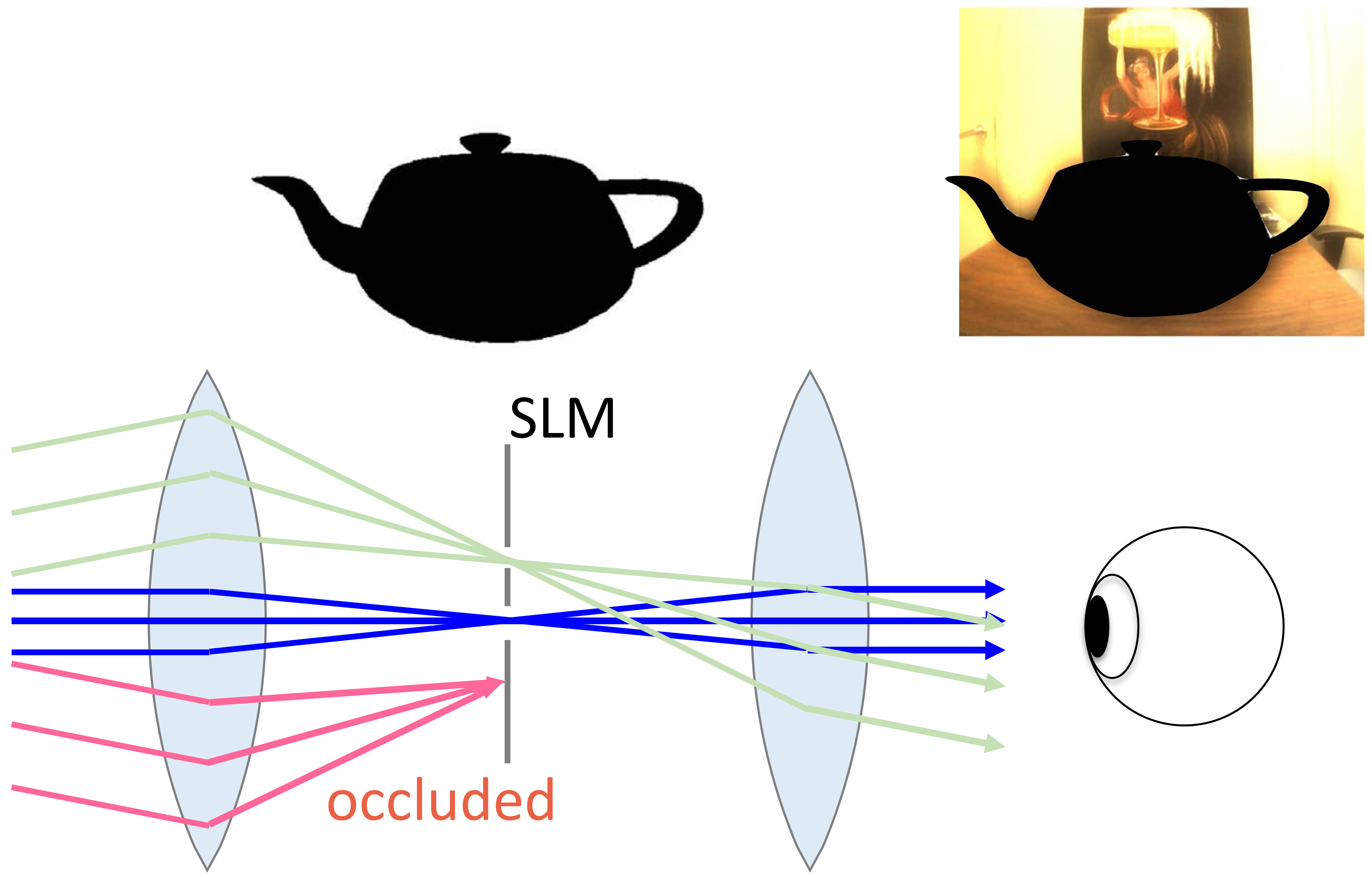


LCD DMD LCOS

Direction Occlusions

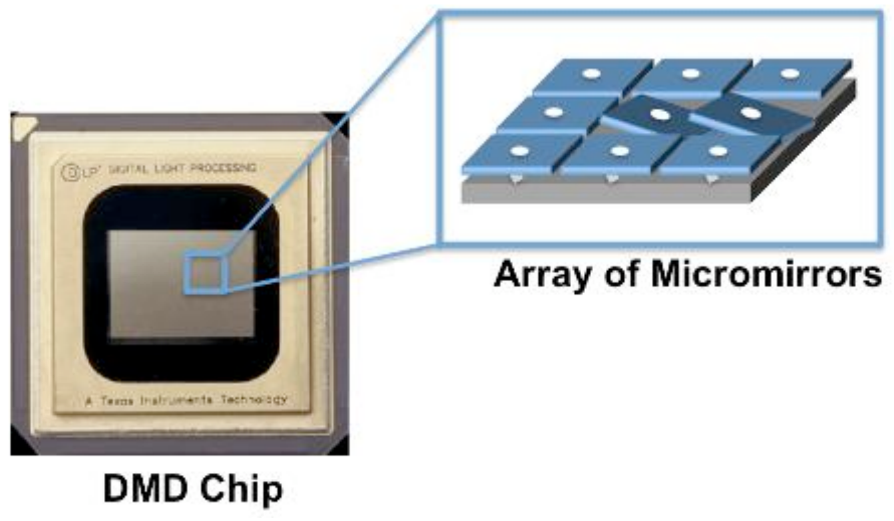


Intermediate imaging occlusions

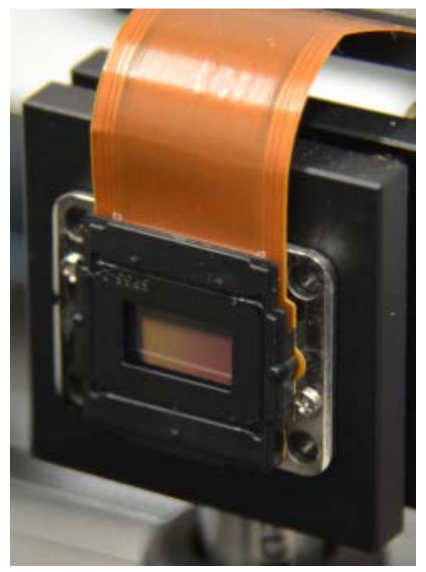


Examples for Spatial Light Modulators (SLMs)

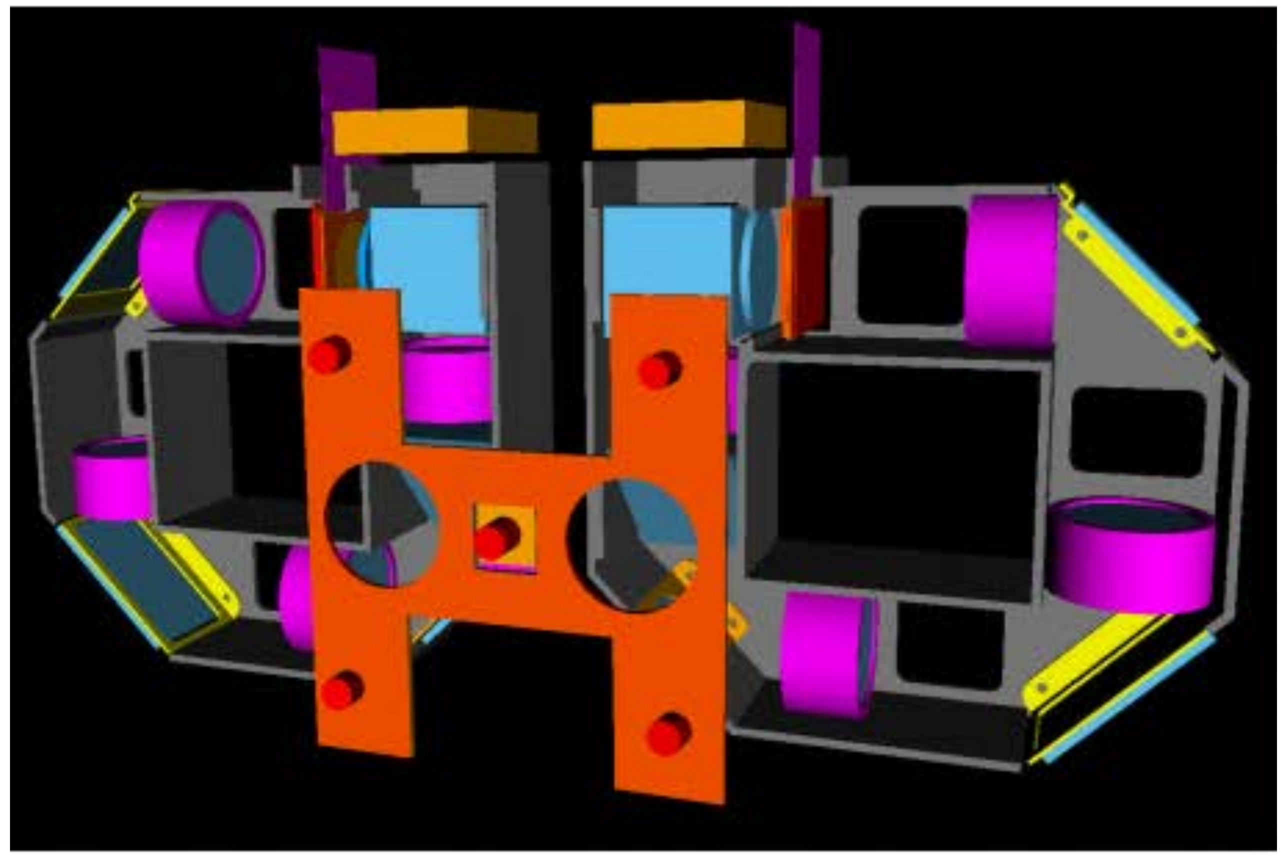
LCD

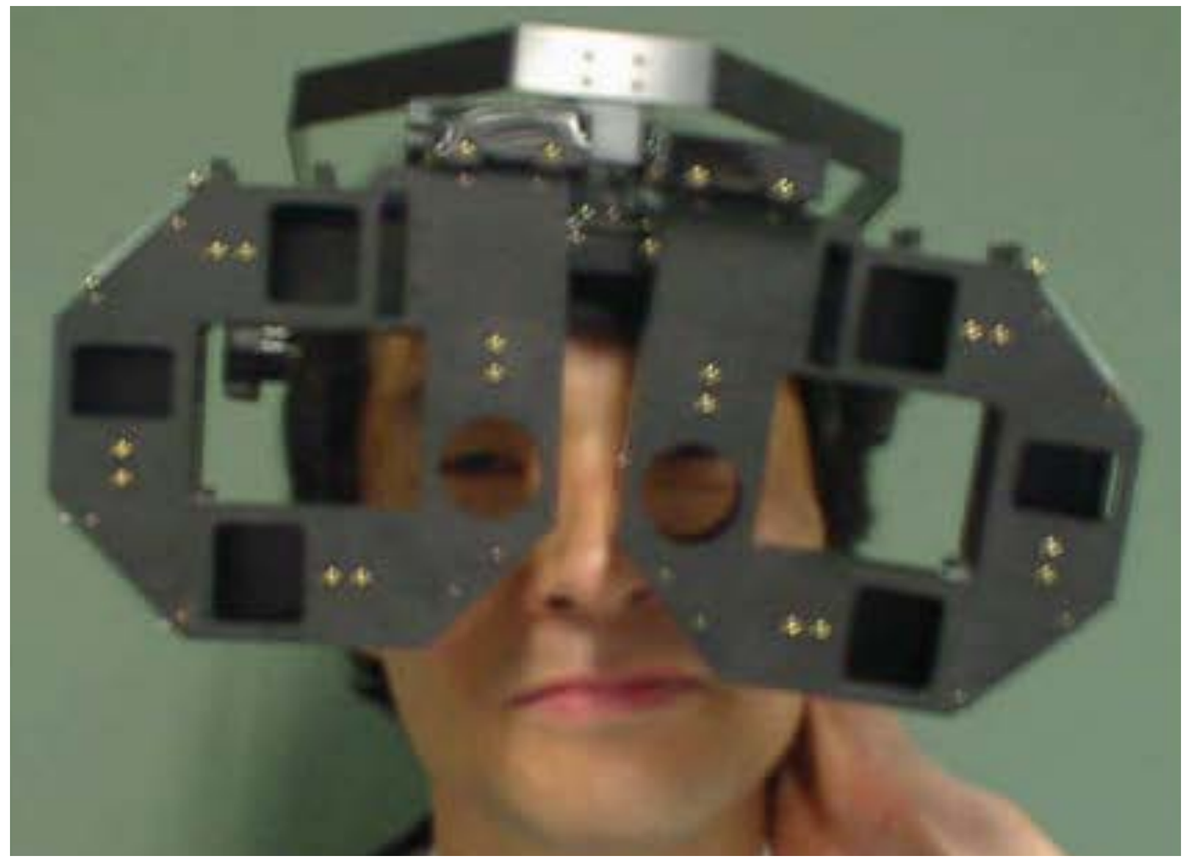


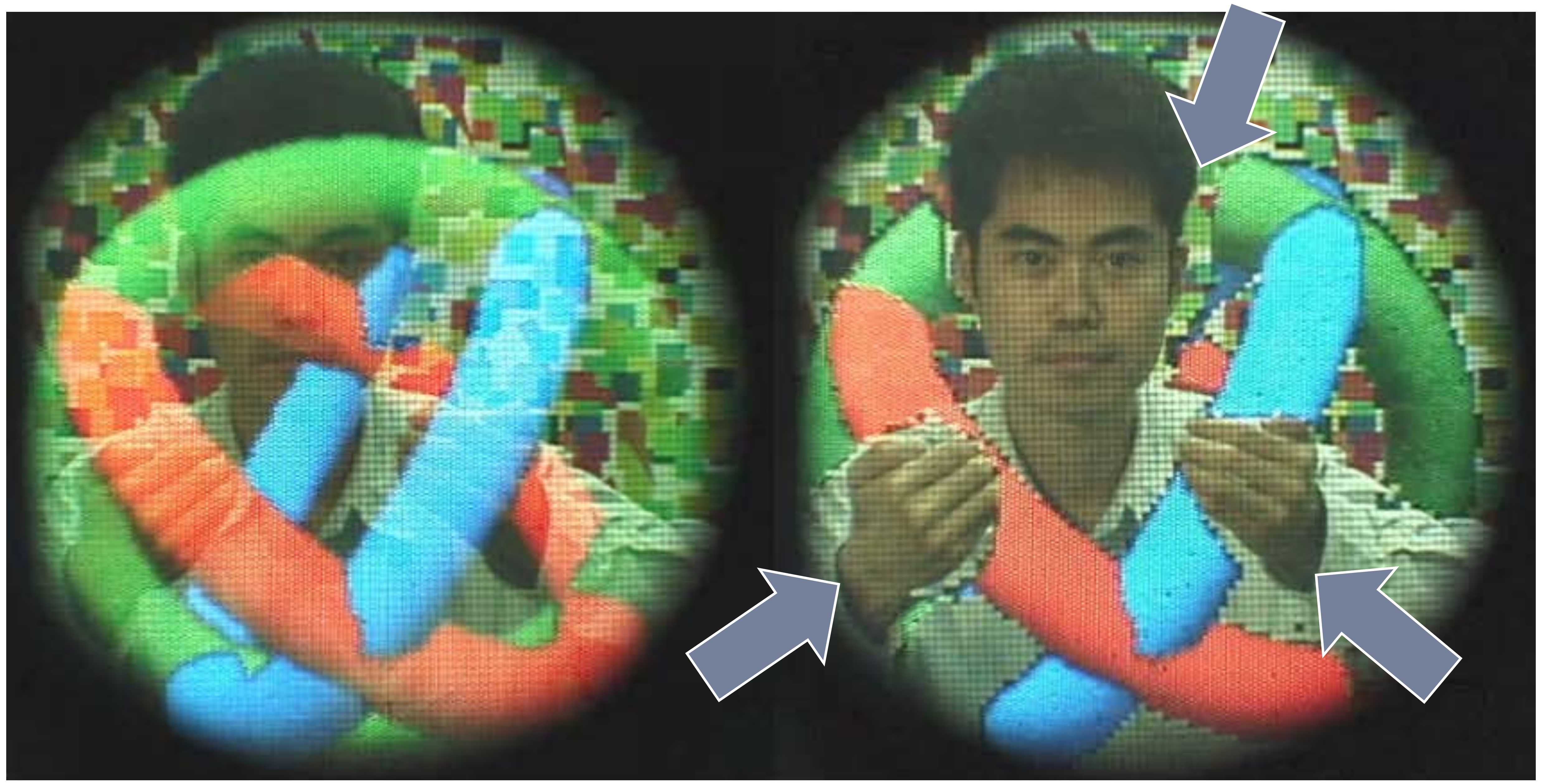
DMD



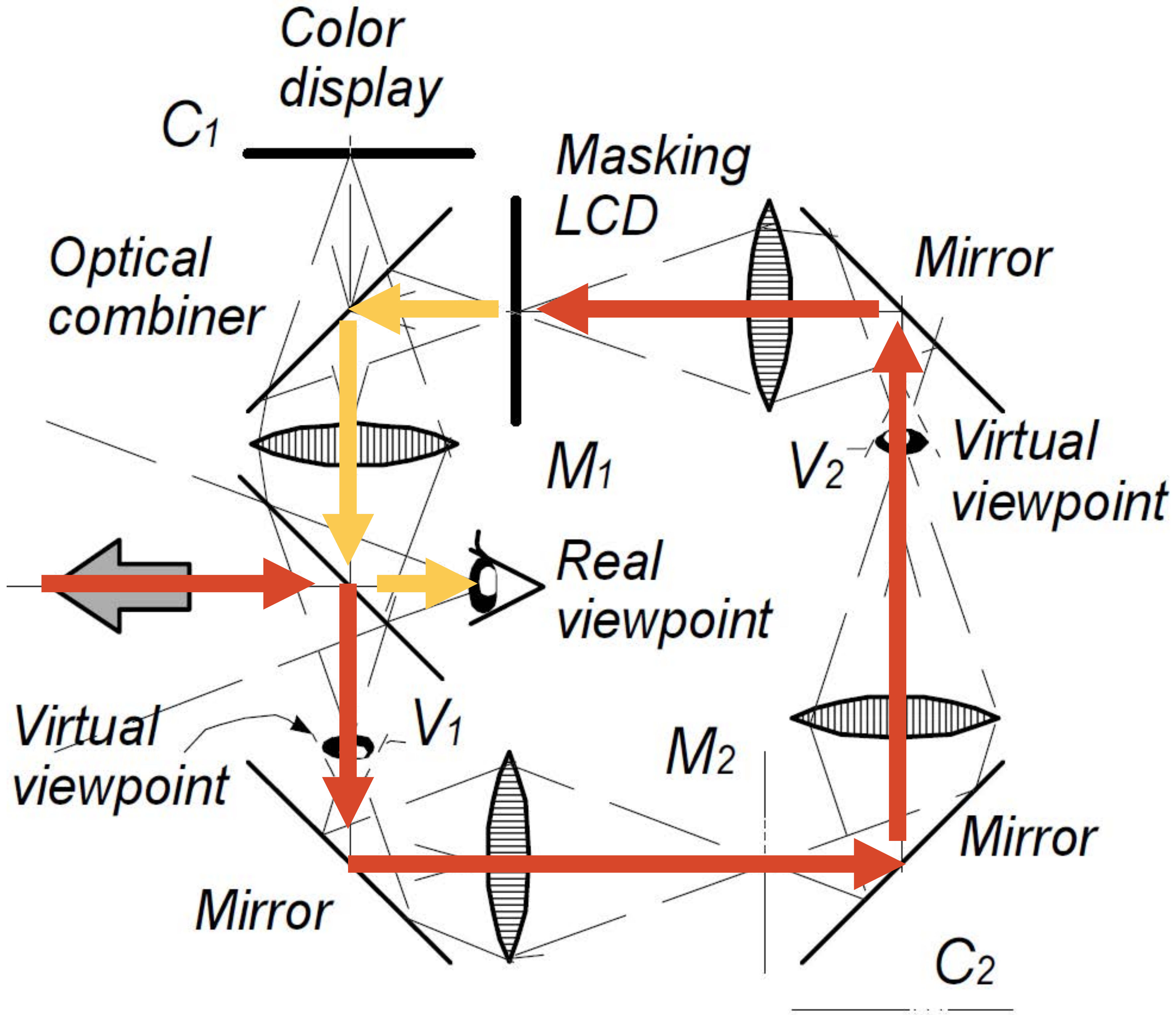
LCOS







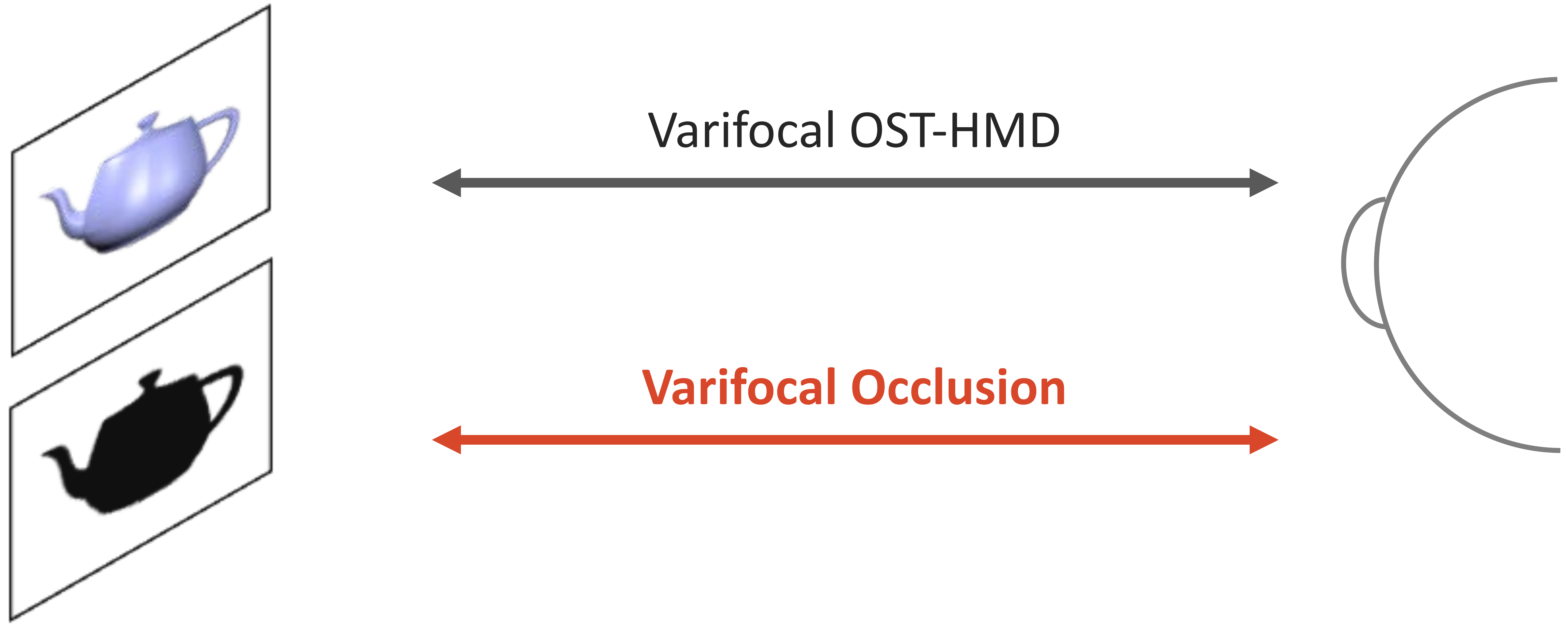
Example for Intermediate imaging occlusions



No viewpoint shift!

Kiyokawa et al. “An occlusion-capable optical see-through head mount display for supporting co-located collaboration” [47]

Visual Realism:
Varifocal Occlusions



Hamasaki and Itoh "Varifocal occlusion for optical see-through head-mounted displays using a slide occlusion mask" [44]

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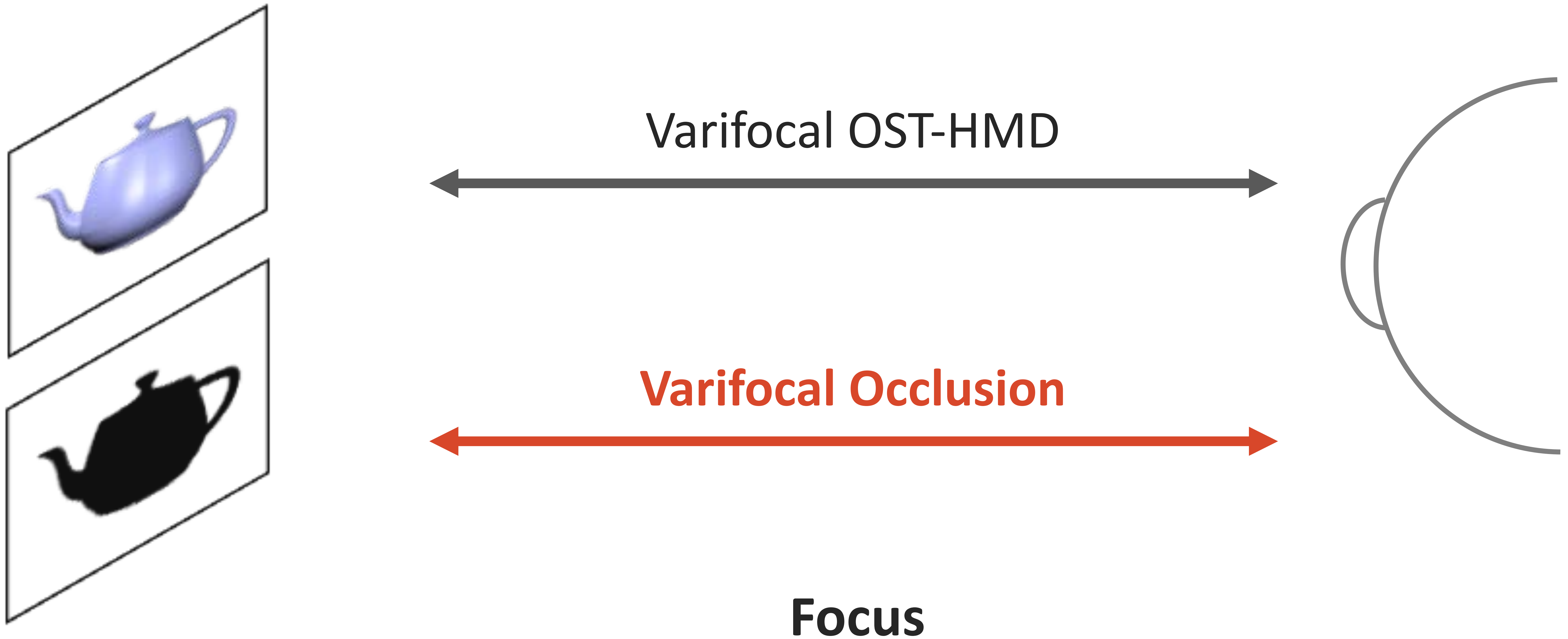
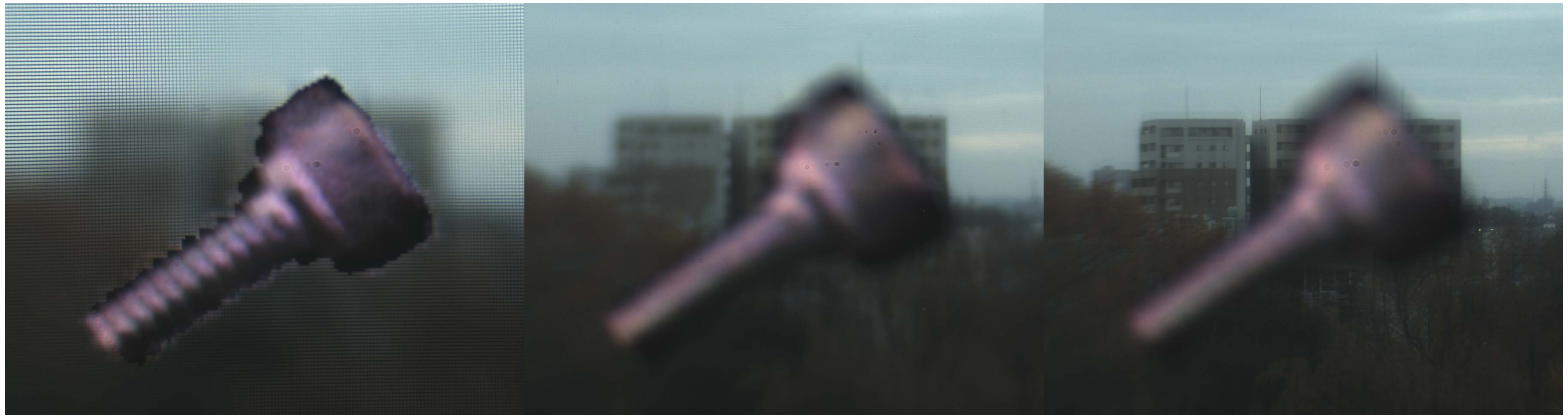


Focus

Near	Middle	Far



Hamasaki and Itoh “Varifocal occlusion for optical see-through head-mounted displays using a slide occlusion mask” [44]

	Occlusion Generation	Adaptive Depth	Varifocal Image	Mask Appearance	Computational Demand	Optical Complexity	Form Factor	Field of View	Portable Prototype
Kiyokawa et al. [75]	LCD	no	no	sharp	low	comlex	bulky	25°	yes
Kiyokawa et al. [74]	LCD	no	no	sharp	low	comlex	bulky	30°	yes
Wilson and Hua [157]	LCoS	no	no	sharp	low	comlex	thin	30.58°	no
Gao et al. [36, 37]	LCoS	no	no	sharp	low	comlex	thin	40°	no
Cakmakci et al. [18]	LCD	no	no	sharp	low	moderate	thin	40°	no
Santos et al. [18]	LCD	no	no	dull	low	N/A	thin	20°	yes
Maimone and Fuchs [103]	LCD	no	yes	dull	high	moderate	thin	65°	yes
Maimone et al. [105]	pinhole display with LCD	yes	yes	dull	moderate	simple	moderate	80°	yes
Itoh et al. [53]	LCD	partially	no	sharp	low	simple	thin	70-80°	no
Yamaguchi and Takaki [161]	LCD with Microlenses	yes	yes	sharp	high	moderate	thin	moderate	no
Uchida et al. [161]	DMD	no	no	sharp	low	comlex	moderate	narrow	no
Kwangsoo et al. [161]	DMD	no	no	sharp	low	comlex	moderate	narrow	no
Krajancich et al. [82]	DMD	yes	no	sharp	high	comlex	moderate	8.7°	no
Hamasaki and Itoh [44]	LCD on linear stage	yes	no	sharp	low	moderate	moderate	narrow	no
Rathinavel et al. [126]	LCD with refocusable lens	yes	yes	sharp	moderate	comlex	moderate	15.3°	no

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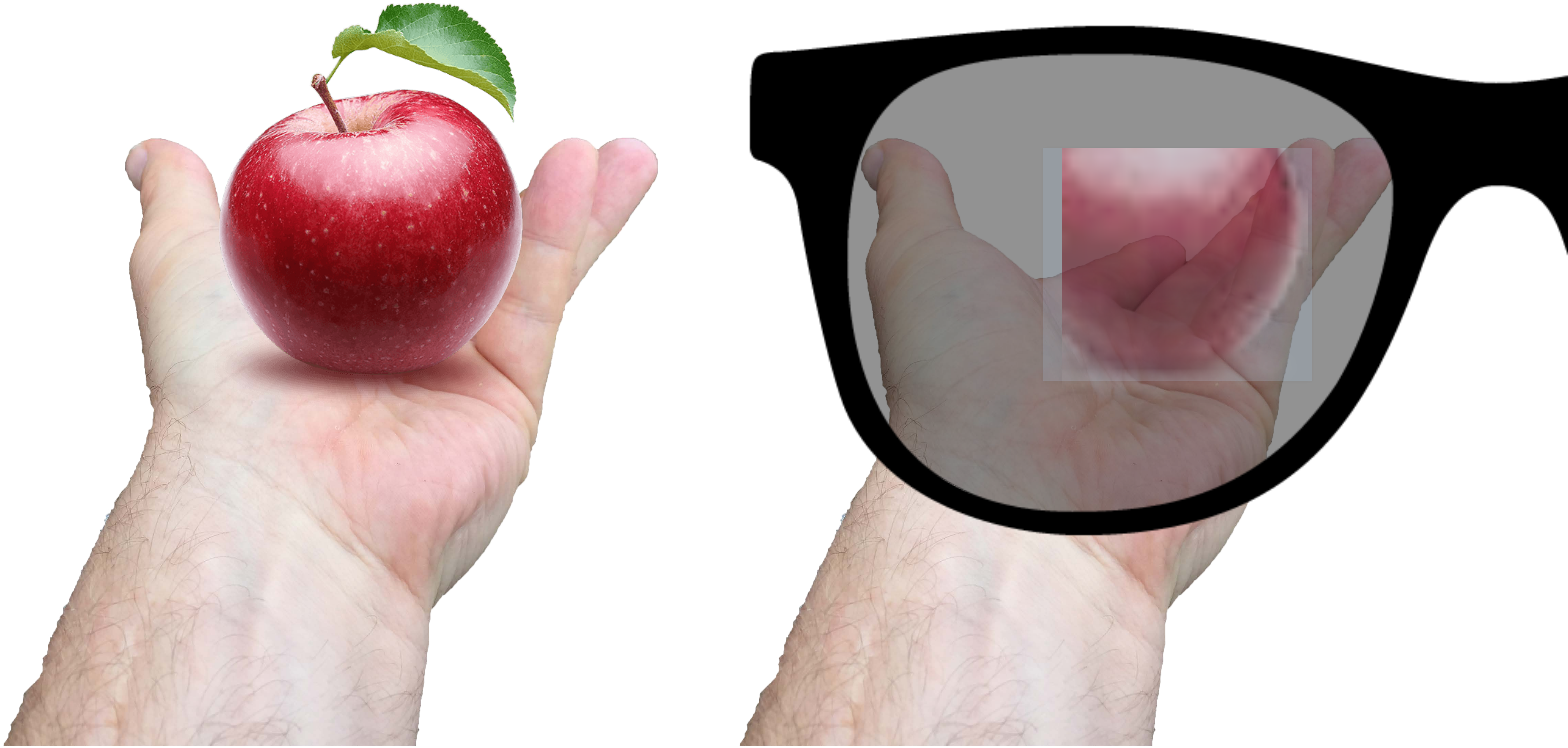

Towards Indistinguishable Augmented Reality in Optical See-Through Head-Mounted Displays

tobias langlotz, yuta itoh, jonathan sutton, alexander plopski

The University of Auckland
UNSW
University of Canterbury
Monash University
University of Otago
The University of Queensland
Victoria University Wellington
University of South Australia

Indistinguishable Augmented Reality on Optical See-Through Head-Mounted Displays

Spatial Realism:

- Spatial calibration
- Distorsion correction

Temporal Realism:

- System Latency
- Display latency and flickr

Visual Realism:

- Colour
- Dynamic range
- Accomodation capability
- Occlusion capability
- Wide field of view
- Resolution

Visual Realism:
Field of View

Overview:

- Overlap in visual field occurs in the nasal visual field and gives an overall horizontal visual field of up to 180 degrees (some state 190 degrees) [47]
- Increases up to 290 degrees when allowing for the movement of the eye within a stationary head [47].

	Mechanism	Classification	See-Through	Field of View	Resolution	Eye Tracking Needed	Optical Complexity	Form Factor	Computational Demand	Miniature Prototype
Lanman and Luebke [93]	microlenses	light-field	no	33.3°	low	yes	simple	thin	moderate	yes
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Otao et al. [118]	microlenses	light-field	no	narrow	low	yes	simple	bulky	moderate	yes
Maimone et al. [105]	pinlight display	always-in-focus	yes	110°	low	recommended	simple	thin	moderate	yes
Akşit et al. [5]	pinhole display	always-in-focus	no	83°	low	recommended	simple	thin	moderate	yes
Song et al. [141]	pinhole display	always-in-focus	yes	narrow	low	recommended	simple	thin	moderate	yes
Jang et al. [61]	laser with steering mirror	holographic	yes	68°	moderate	yes	complex	thin	high	yes
Maimone et al. [104]	SLM	holographic	yes	80° horizontal	high	yes	complex	thin	moderate	yes
Shi et al. [140]	SLM	holographic	no	N/A	high	yes	complex	moderate	high	no
Moon et al. [111]	SLM	holographic	yes	narrow	N/A	yes	complex	moderate	high	yes
Huang et al. [50]	stacked LCD panels	multi-plane	no	125°	high	no	simple	bulky	high	yes
Lee et al. [95]	savart plate	multi-plane	yes	37°	high	no	moderate	moderate	low	yes
Yoo et al. [162]	polarized lenses	multi-plane	yes	7.5° horizontal	high	no	moderate	moderate	low	no
Liu et al. [102]	polymer stabilized scattering shutters	multi-plane	yes	narrow	N/A	no	simple	moderate	low	no
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Liu et al. [101]	focus tunable lens	varifocal	yes	28°	moderate	no	complex	moderate	low	no
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Wilson and Hua [158]	alvarez lens	varifocal	yes	103°	moderate	no	complex	moderate	moderate	no
Matsuda et al. [107]	SLM	focal surface	no	18°	high	yes	complex	bulky	high	yes

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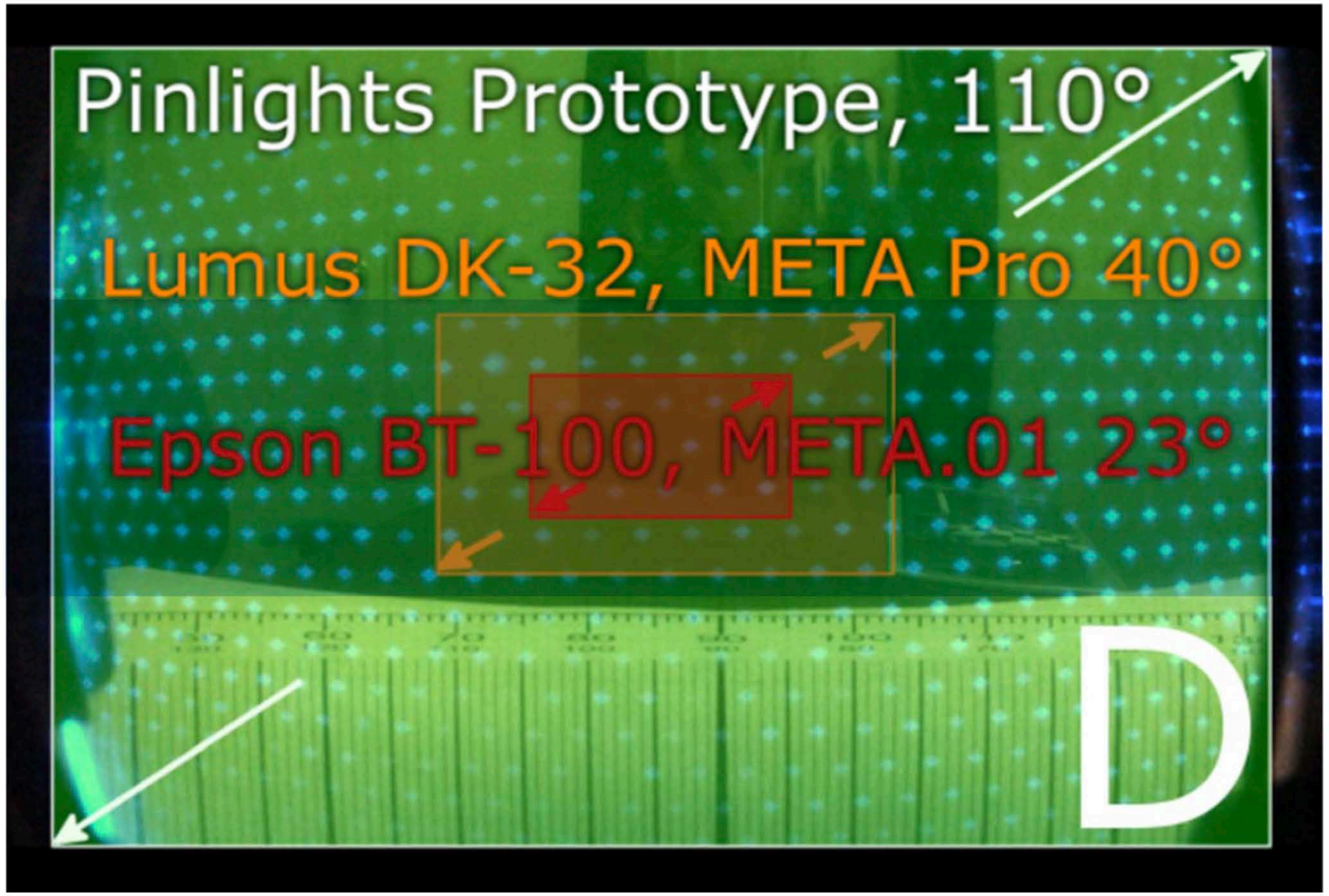

Maimone et al. “Pinlight Displays: Wide Field of View Augmented Reality Eyeglasses using Defocused Point Light Sources” [105]

Visual Realism: Resolution

High resolution:

- Field of View: 190 by 120 degrees
- Resolution: 60 cycles per degree
- Overall: 22800 x 14400 pixel and 328.3 megapixels (with >90Hz)

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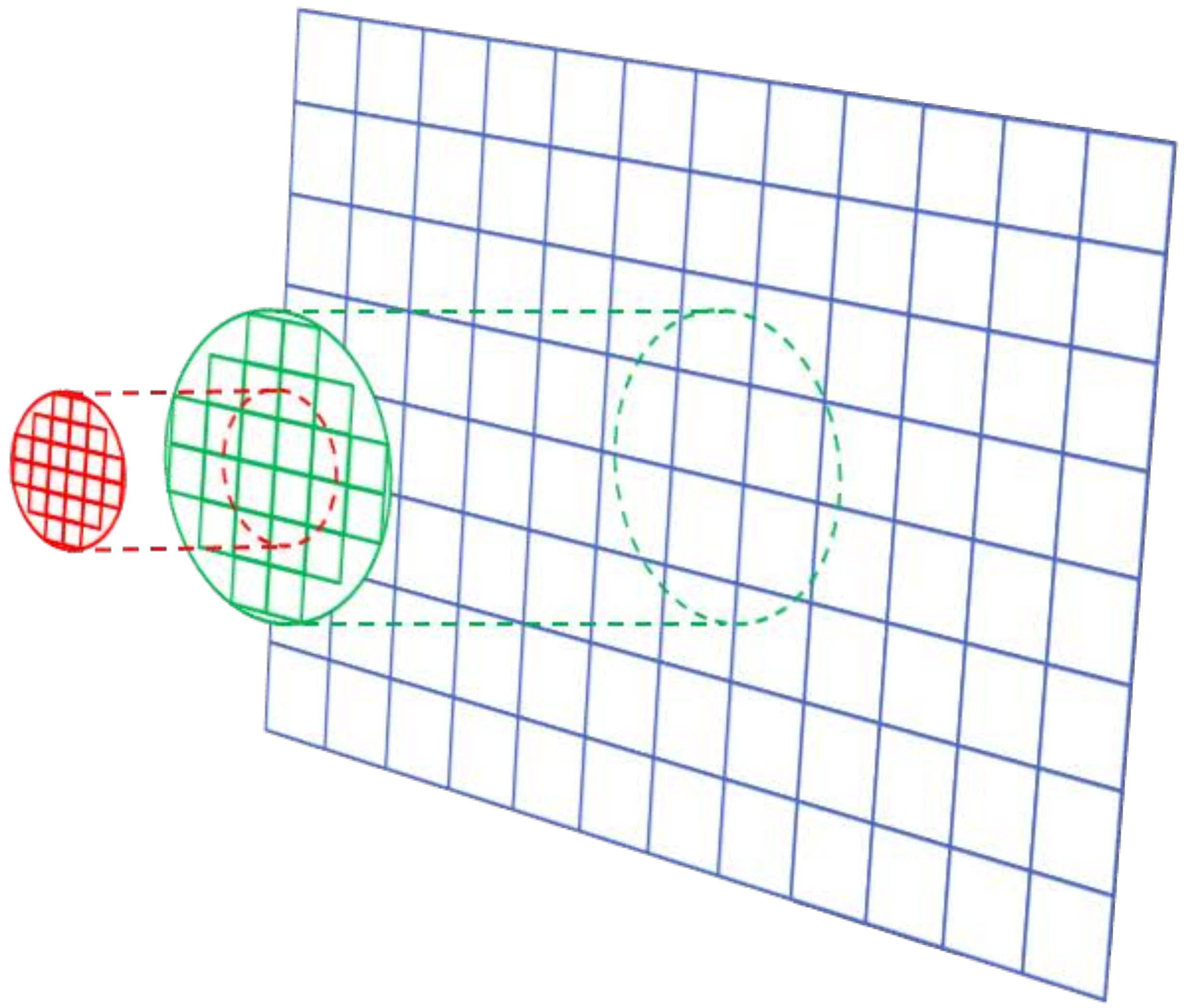

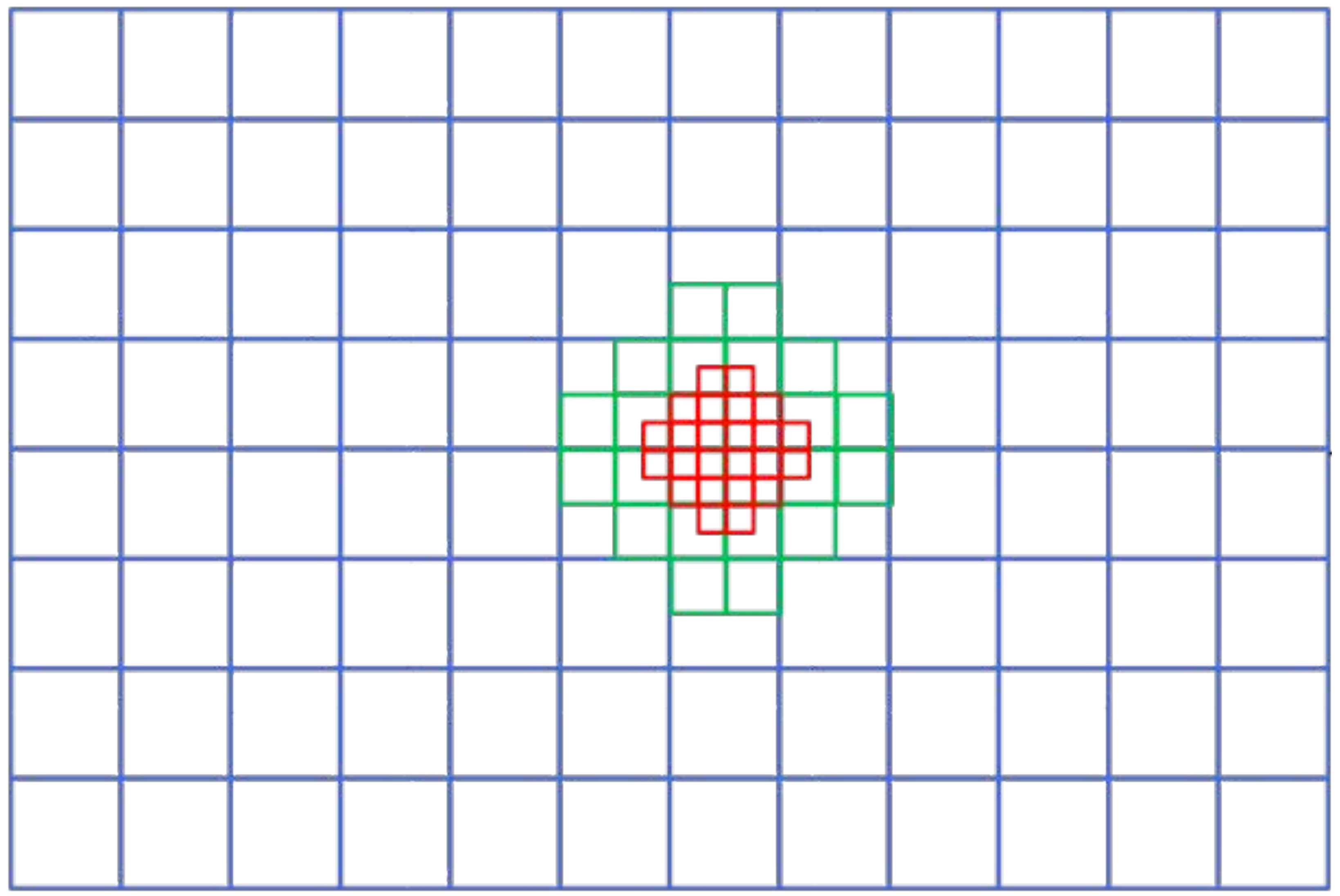

High resolution:

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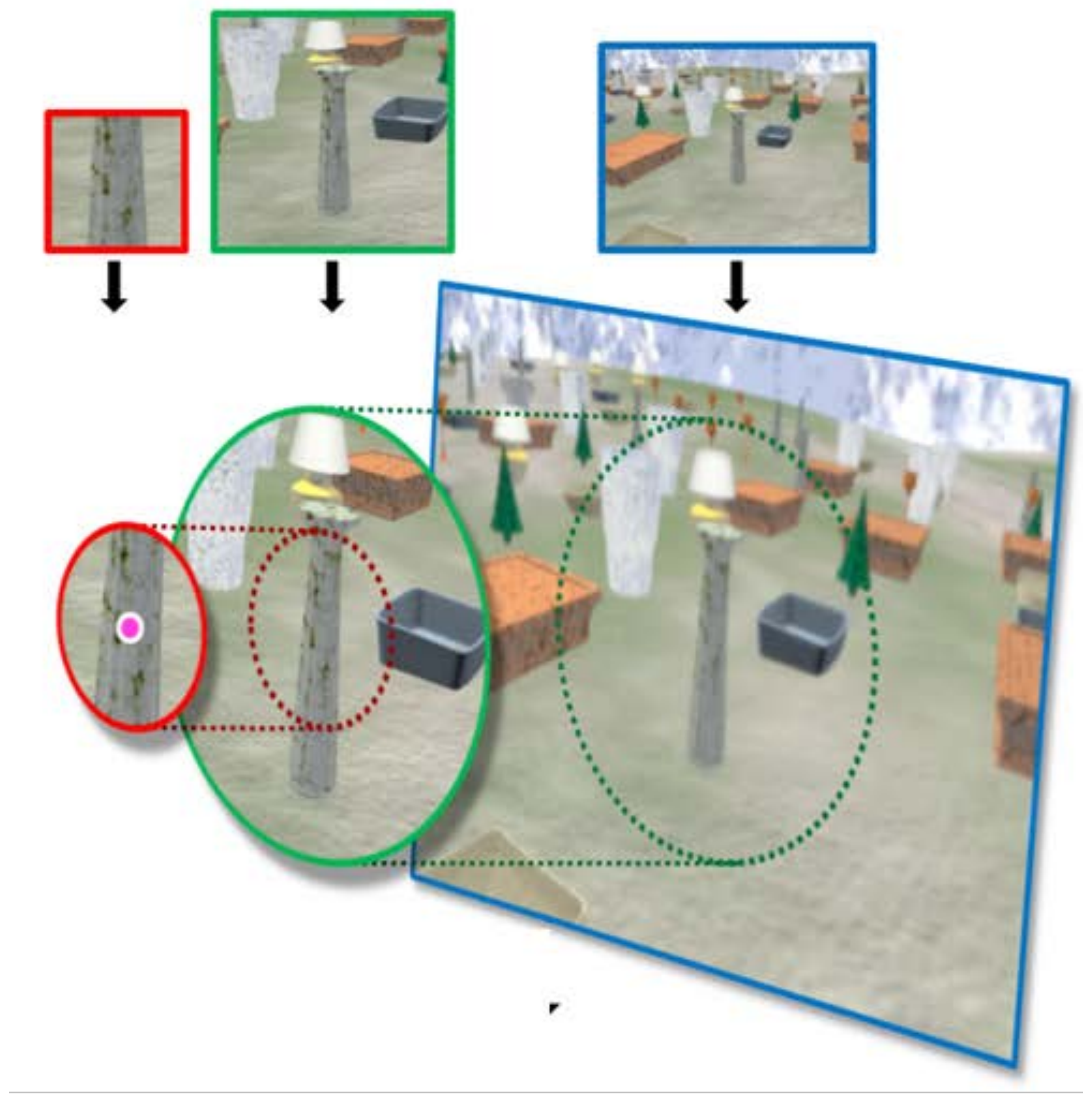

Guenter et al. "Foveated 3D Graphics". [42]

Summary

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- Lots of issues but also promising progress
- Promising future directions:
  - Full light controll in OST HMDs (adding light and filtering environment light)
  - Research that successfully tackles several issues
  - Research that demonstrate potential for wearable form factor
  - Great example:

Kim et al. “Foveated AR: Dynamically-Foveated Augmented Reality Display” [67]

- Current technology are still amazing pieces of engineering!

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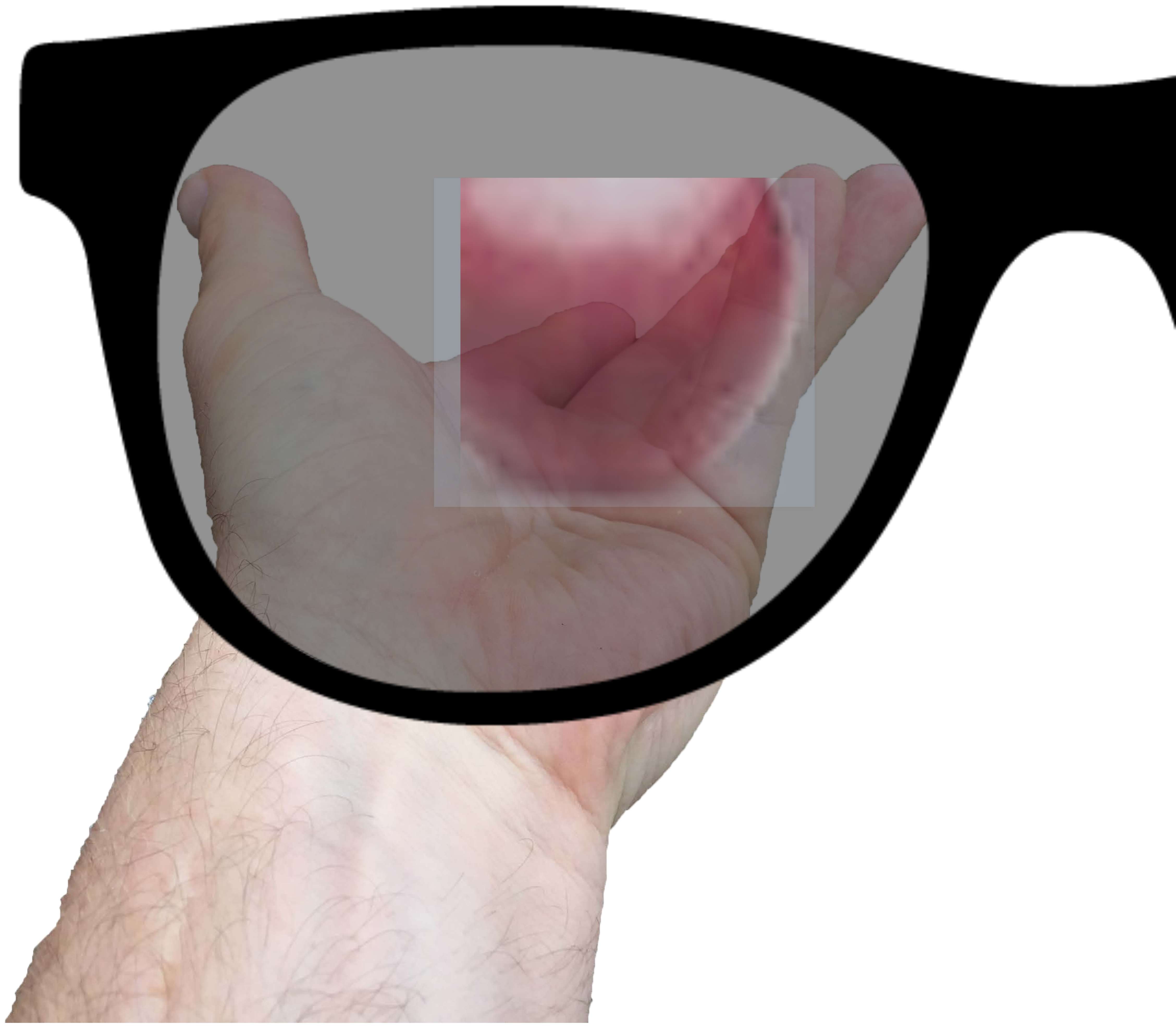

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References:

[1] 1995. *Foundations of Vision.* Sinauer Associates.
[2] 2002. *Display Interfaces:Fundamentals and Standards.* John Wiley & Sons.
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