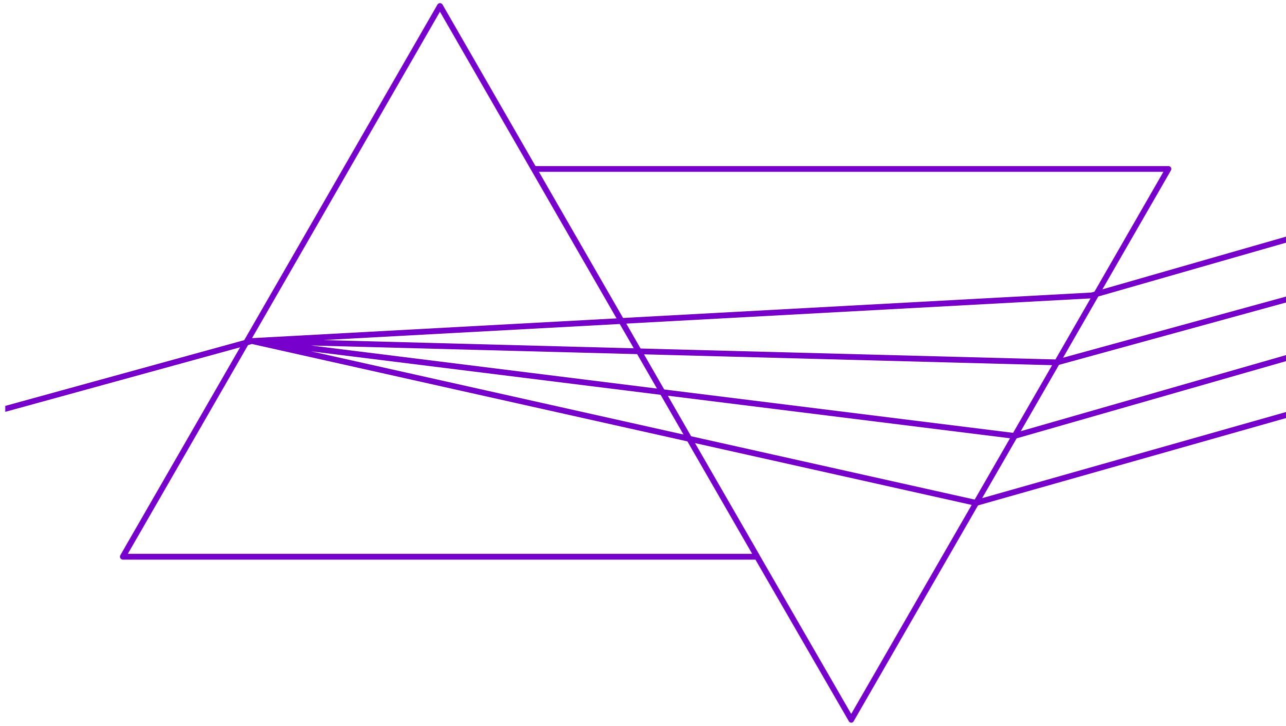
OPTICA
Advancing Optics and Photonics Worldwide
Formerly OSA

Novel Displays for Future Vision Science



Technical Group Executive Committee

Karen Hampson
University of Oxford

Laura Young
University of Newcastle

Maria Vinas
MGH-Harvard Medical School

About Our Technical Group

Our technical group is interested in encoding and displaying visual information, new technologies for visual displays and understanding and treating diseases affecting the visual system and ophthalmic optics.

Our mission is to connect the 1400+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Vision and Color Summer Data Blast Series
- Virtual coffee break at FiO
- Beginners Guide to Adaptive Optics Webinar

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/va
- On Twitter at #VisualScienceTG
- On LinkedIn at www.linkedin.com/groups/4739080/
- Email us at TGactivities@optica.org

Technical Group Executive Committee

Ali Özgür Yöntem
Chair
University of Cambridge

Kai-Han Chang
Chair-elect
General Motors, R&D

Kaan Akşit
University College London

Edward Buckley
Facebook Reality Labs

Golshan Coleiny
Fundamental Optical Solutions

About Our Technical Group

Our technical group focuses on all aspects related to the display technologies, new devices architecture, evolving field of 3D displays, holography, light field and immersive technologies such as AR/VR/MR. We also extend the interest to related topics such as graphics rendering, content, and interactions for these interfaces.

Our mission is to connect the 1k+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Incubator Meeting on Perception in Immersive Technologies
- Incubator Meeting: Visual Perception in AR/VR
- Depth Perception in AR/VR: Optics, Graphics and Content Virtual Panel Discussion
- Display Calibration for Internet and At-home Human Vision, Visual Perception and Color Research

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Ways to connect with us:

- Our website at www.optica.org/it
- On LinkedIn at www.linkedin.com/groups/12205201/
- On Facebook at www.facebook.com/groups/opticadisplaytechnology
- Email us at TGactivities@optica.org

Today’s Speakers

Allie C. Hexley
University of Oxford

Ryuji Hirayama
University College London

Ali Özgür Yöntem
University of Cambridge

OPTICA | Formerly OSA
Technical Groups

The design, potential, and challenges of multi-primary high dynamic range displays for vision science

Allie C. Hexley
Department of Experimental Psychology
University of Oxford, Oxford, UK

Tuesday 28th September 2021
Novel Displays for Future Vision Science Webinar

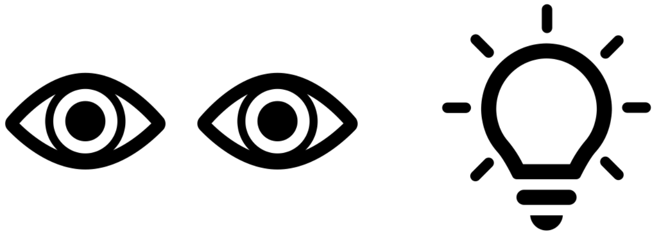
Outline

- What are we trying to (and what are we actually able to) reproduce with displays?
- The RealVision MPHDR
- Metrics for evaluating future display technology

Outline

- **What are we trying to (and what are we actually able to) reproduce with displays?**
- The RealVision MPHDR
- Metrics for evaluating future display technology

What happens when we see light?



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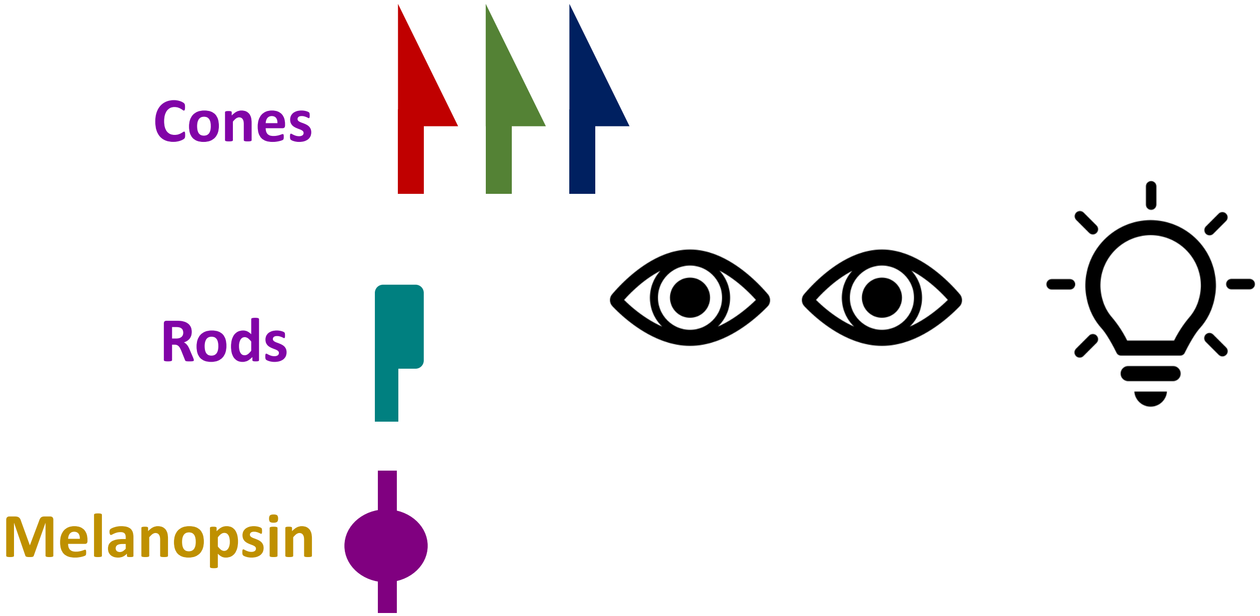

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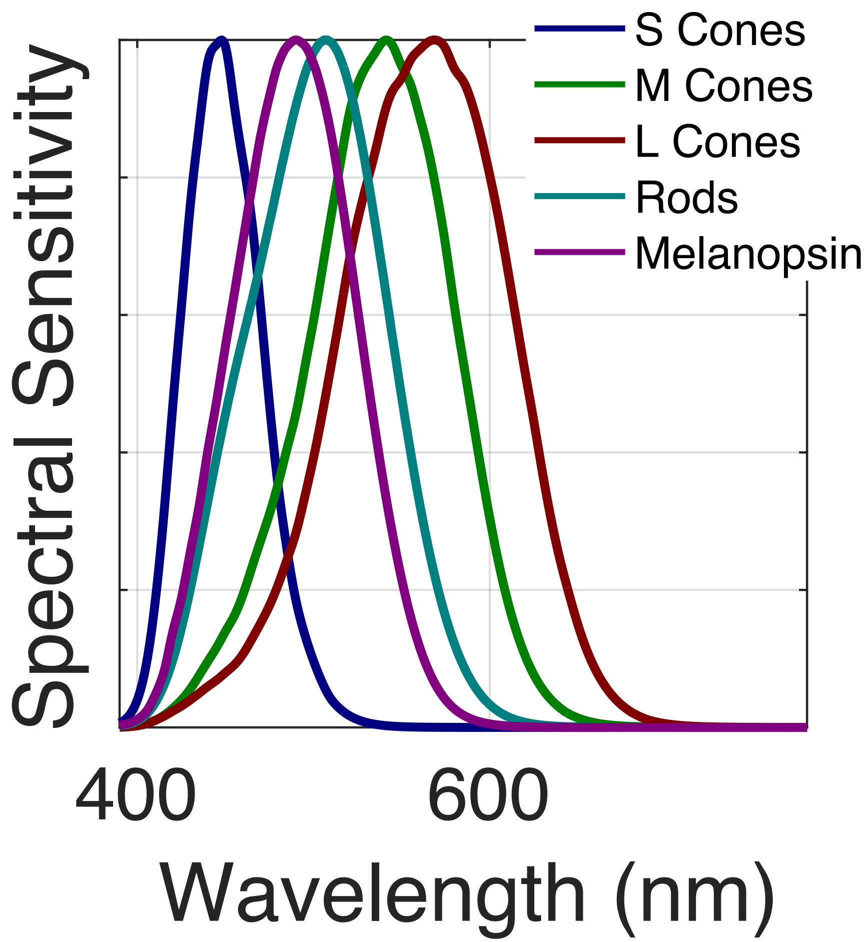

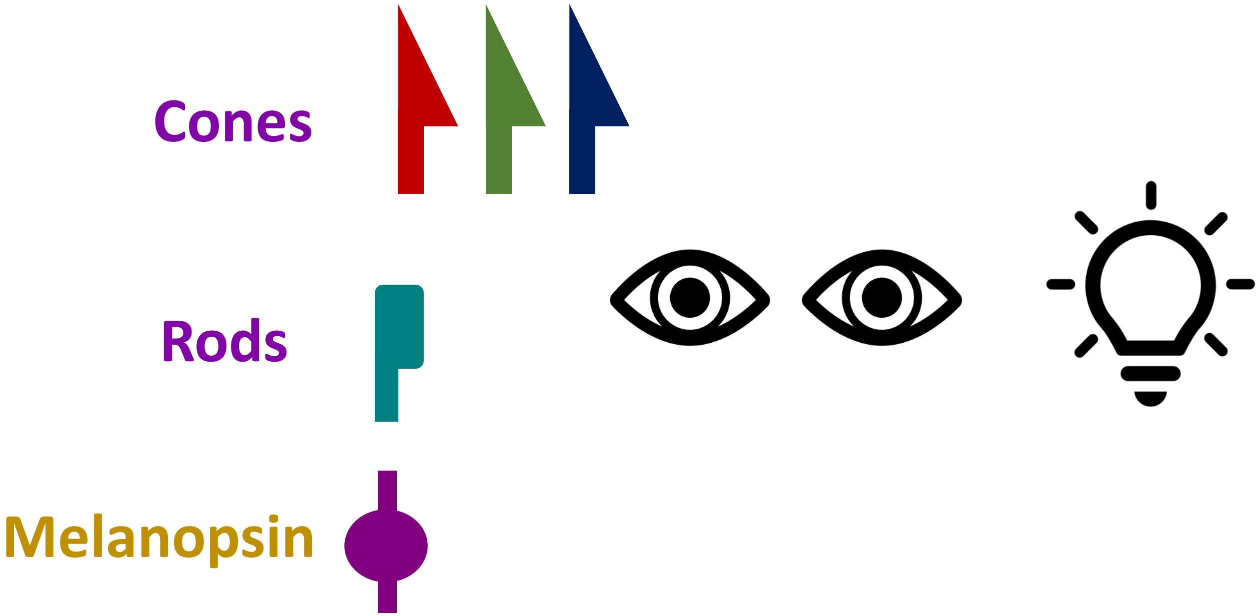

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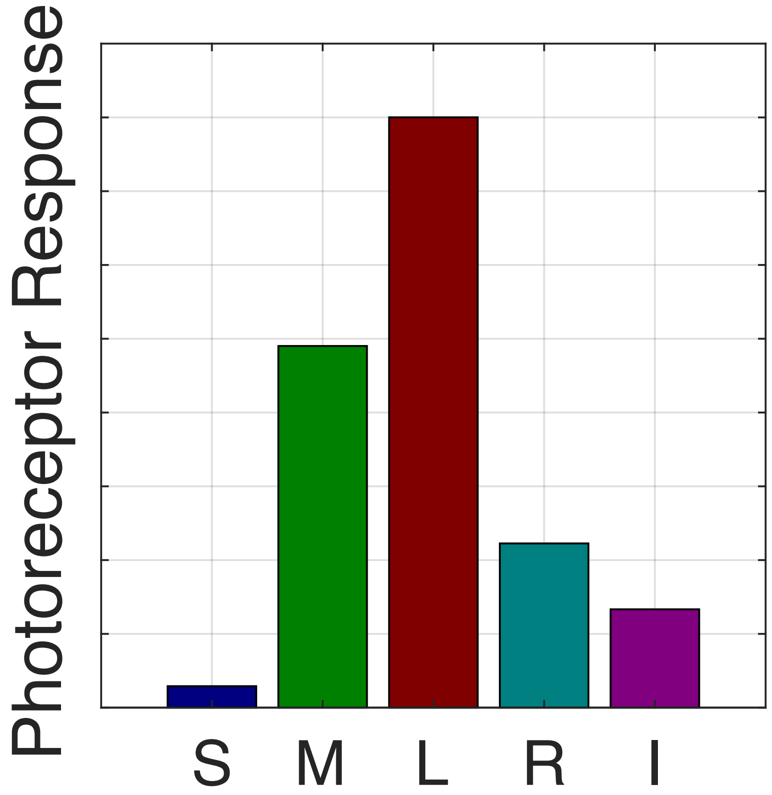

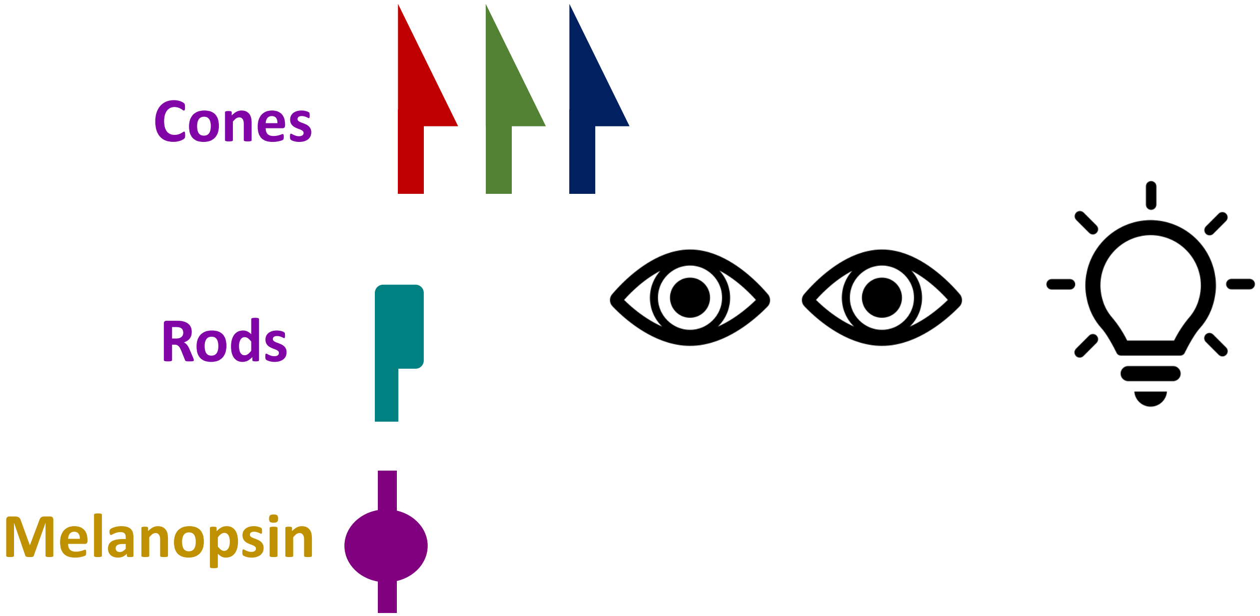

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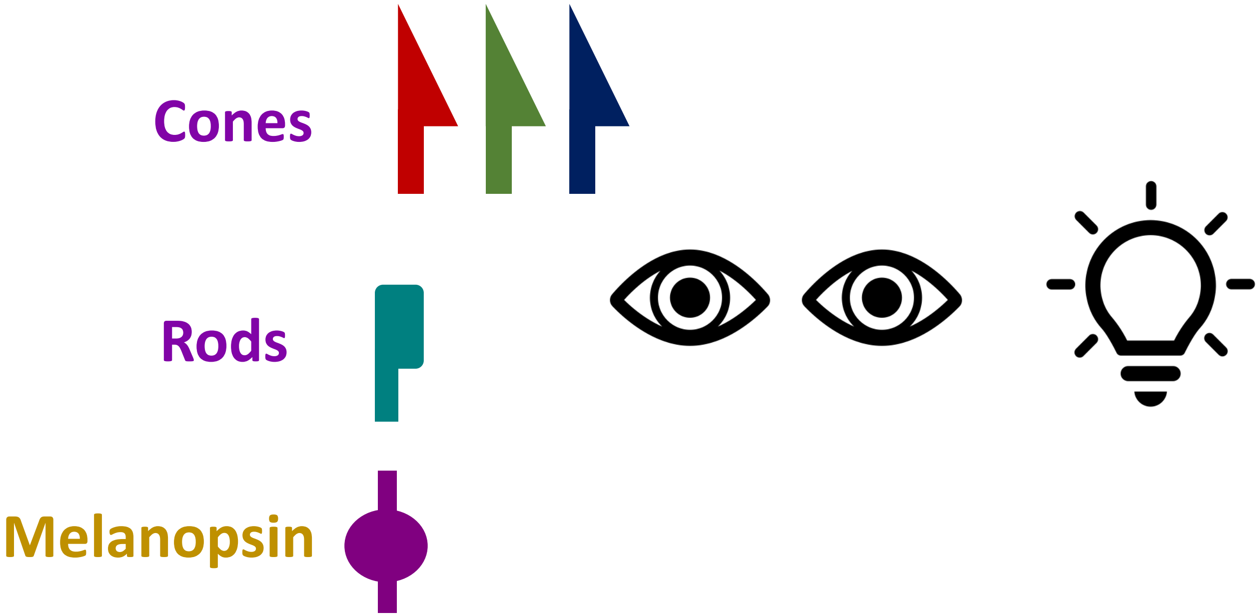

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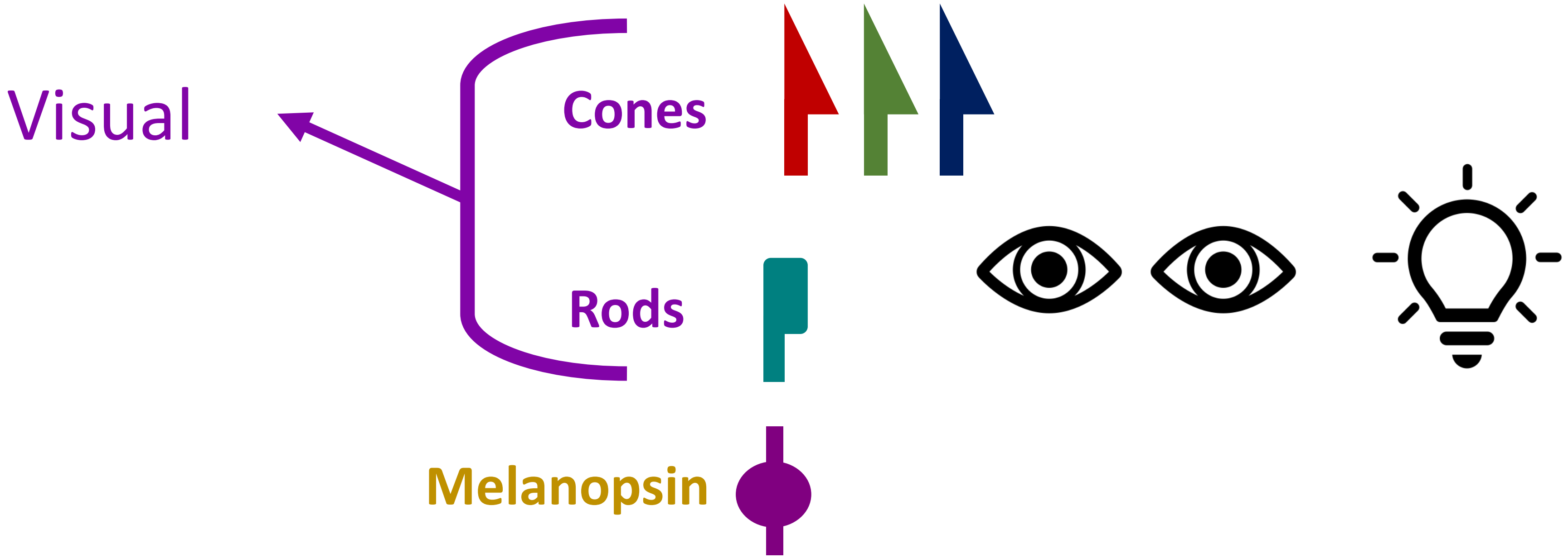

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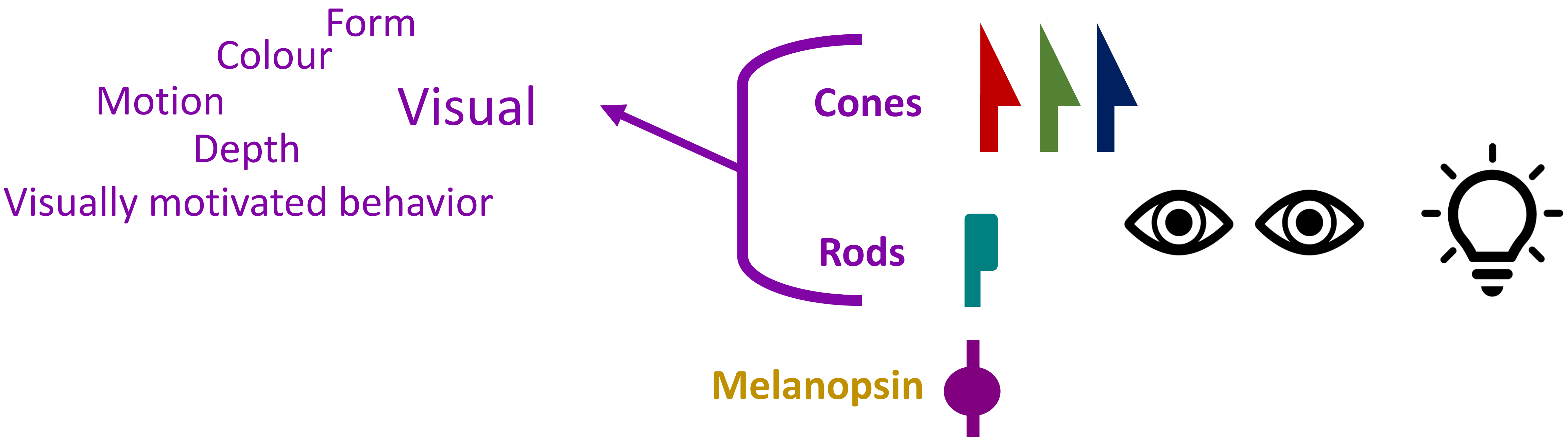

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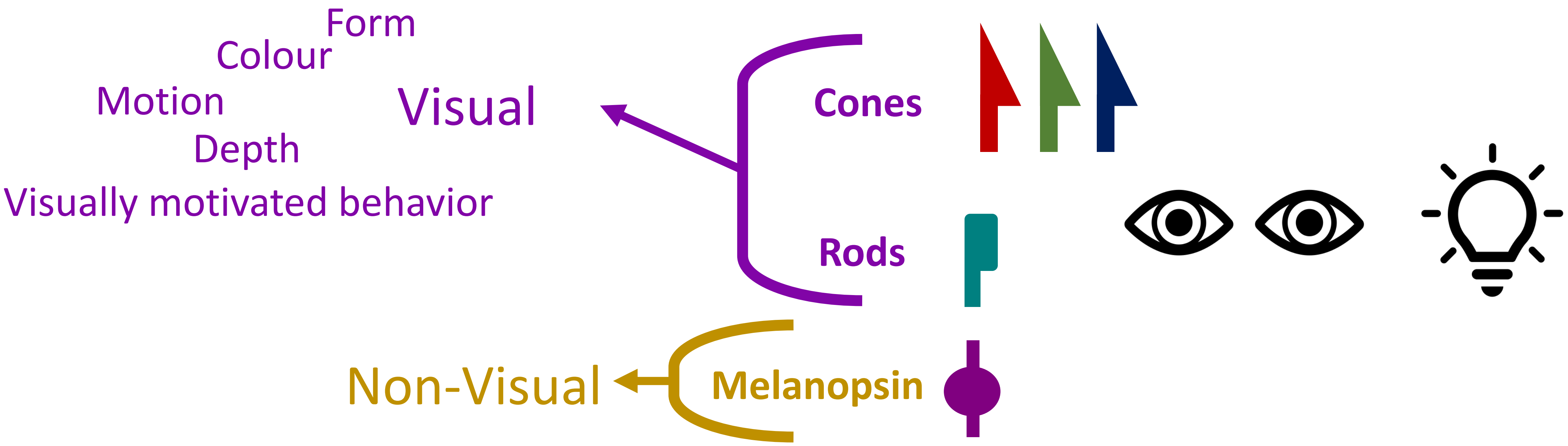


Cajochen et al., 2011; Rollag et al., 2003; Brainard et al., 2001; Brown et al., 2012; Yamakawa et al., 2019; McGougal et al., 2010; Spitschan, 2019.

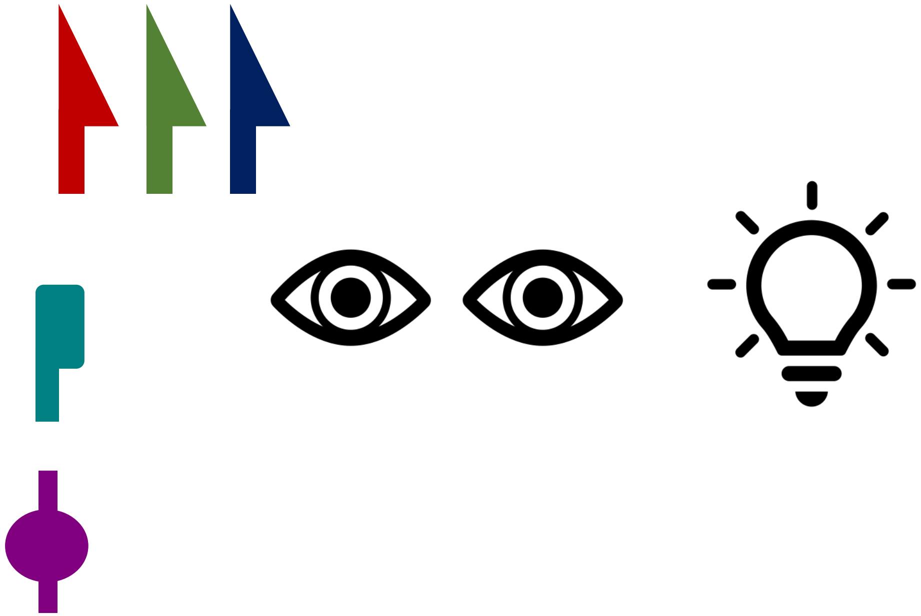
What happens when we see light?

Form
Colour
Motion
Depth
Visually motivated behavior

Visual

Cones

Rods



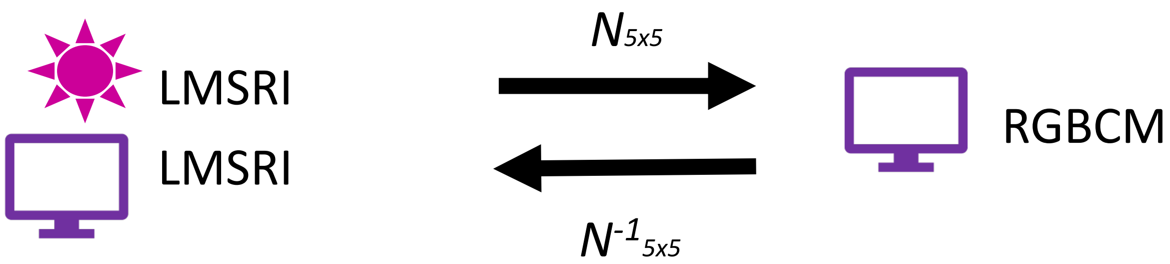
Sleep-wake control
Circadian rhythm
Pupil size
Mood

Non-Visual

Melanopsin

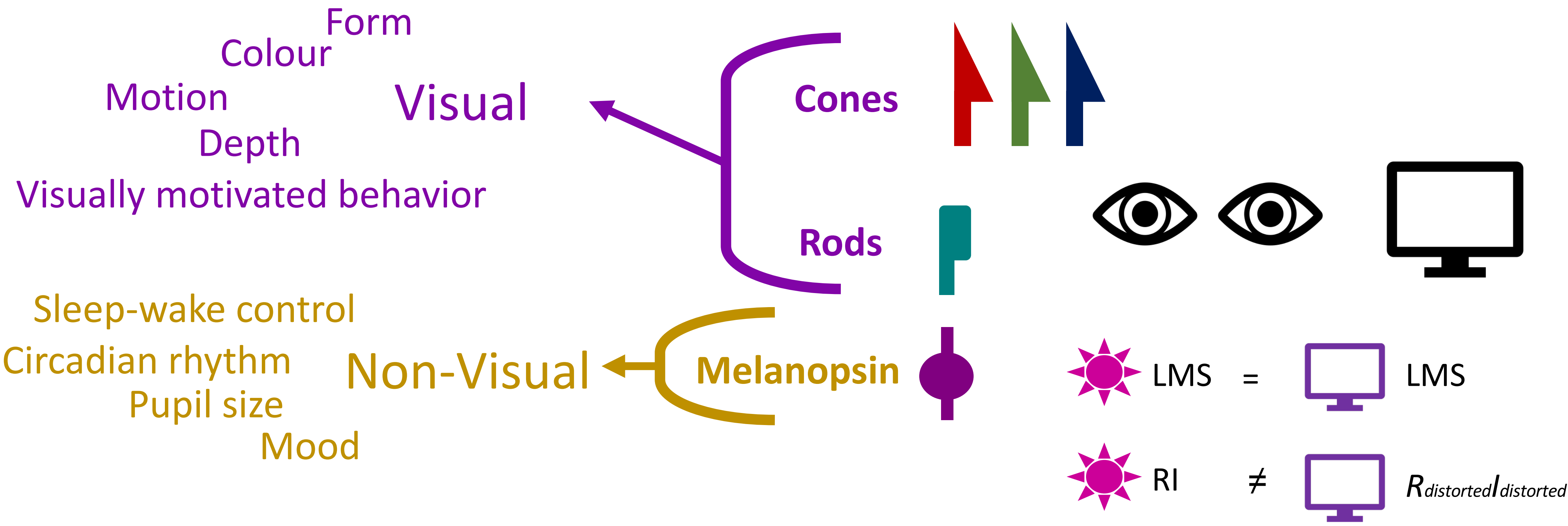
Cajochen et al., 2011; Rollag et al., 2003; Brainard et al., 2001; Brown et al., 2012; Yamakawa et al., 2019; McGougal et al., 2010; Spitschan, 2019.

Five photoreceptor reproduction needs five primary displays



Pokorny et al., 2004; Cao et al., 2015

What’s reproduced on displays?



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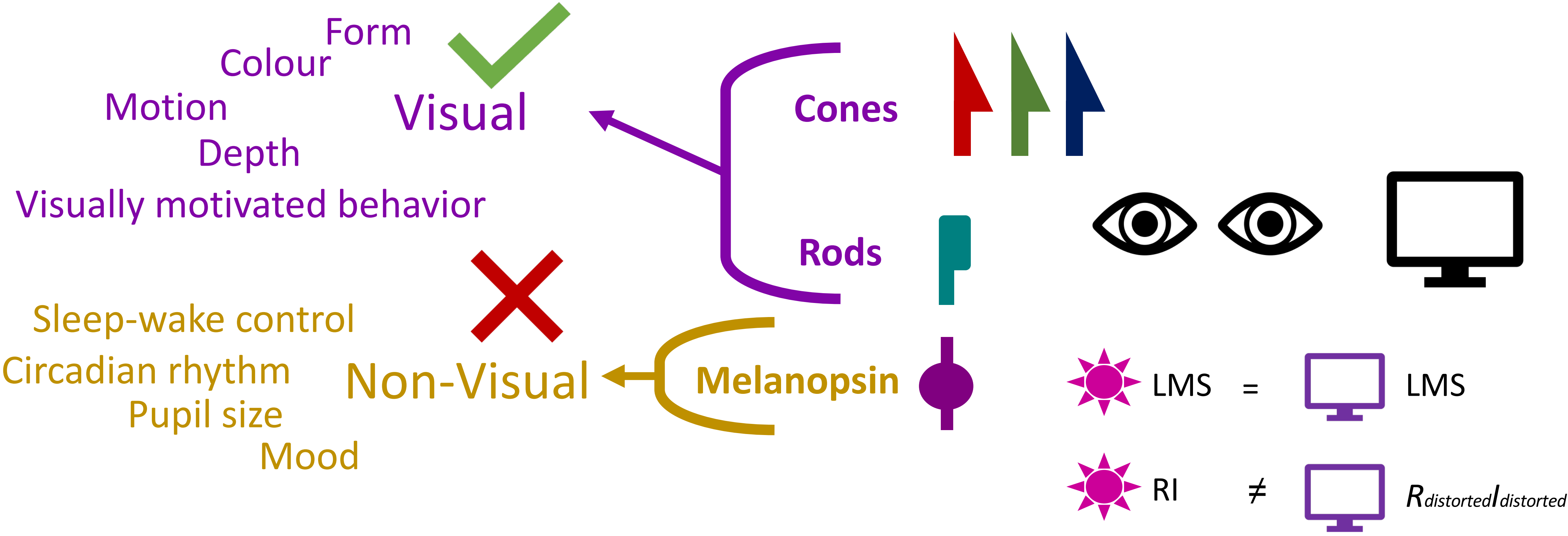

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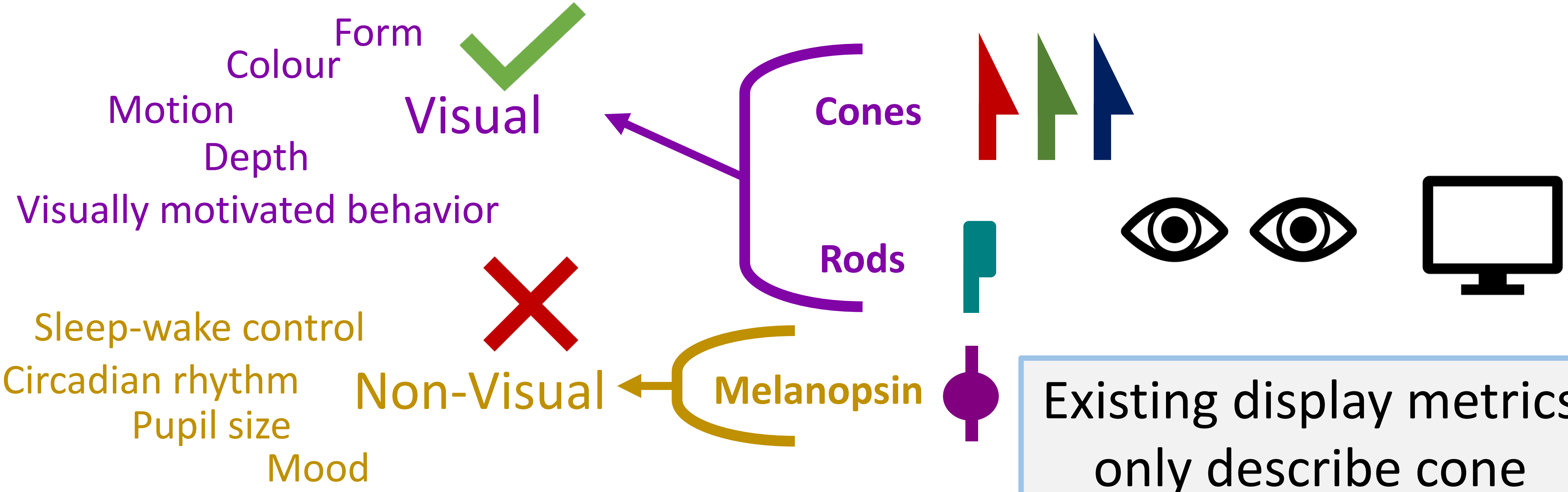
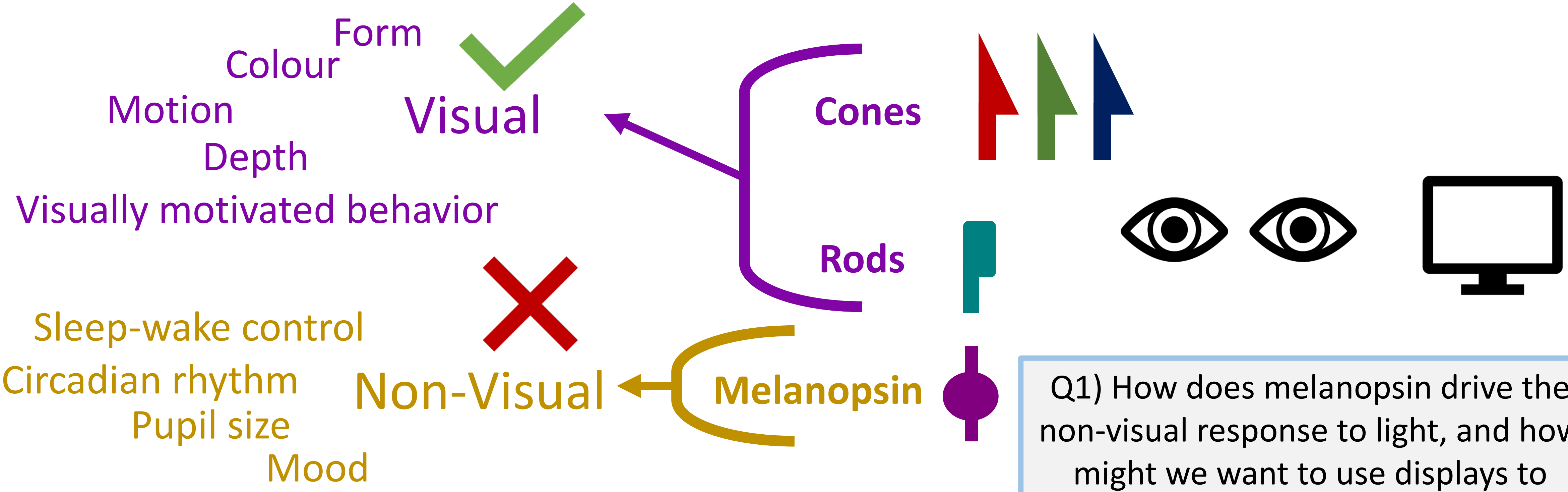


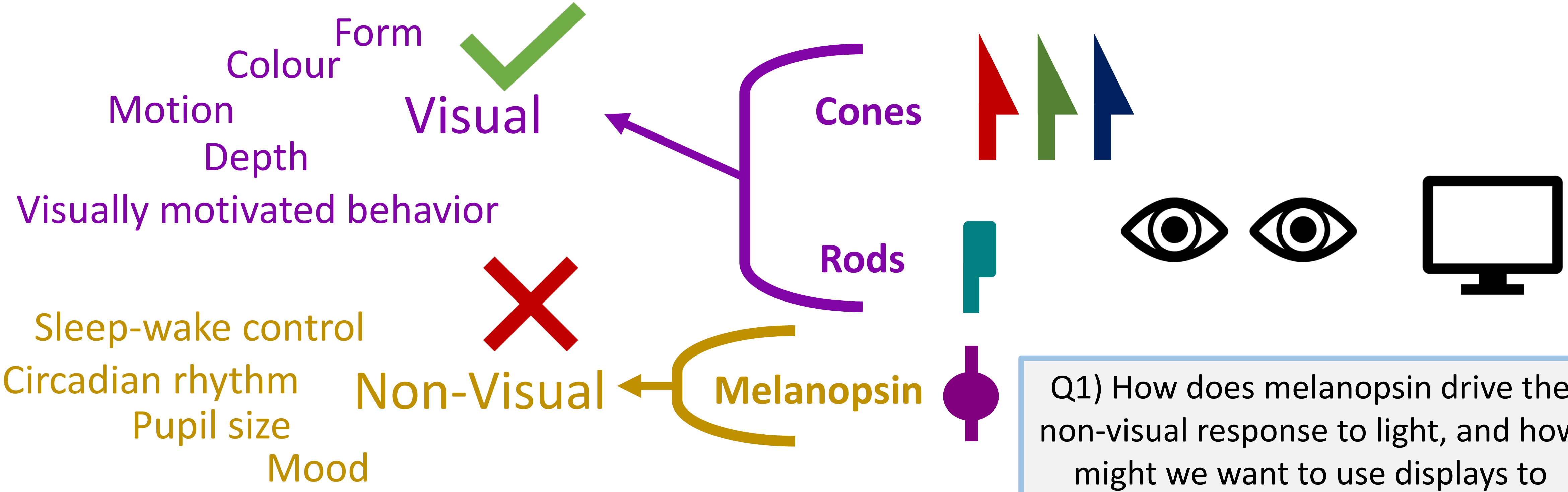
Existing display metrics only describe cone signal reproduction

What's reproduced on displays?



Q1) How does melanopsin drive the non-visual response to light, and how might we want to use displays to control melanopsin?

What’s reproduced on displays?



Q1) How does melanopsin drive the non-visual response to light, and how might we want to use displays to control melanopsin?

The RealVision MPHDR

What's reproduced on displays?

Form
Colour
Motion
Depth
Visually motivated behavior

Visual

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Rods

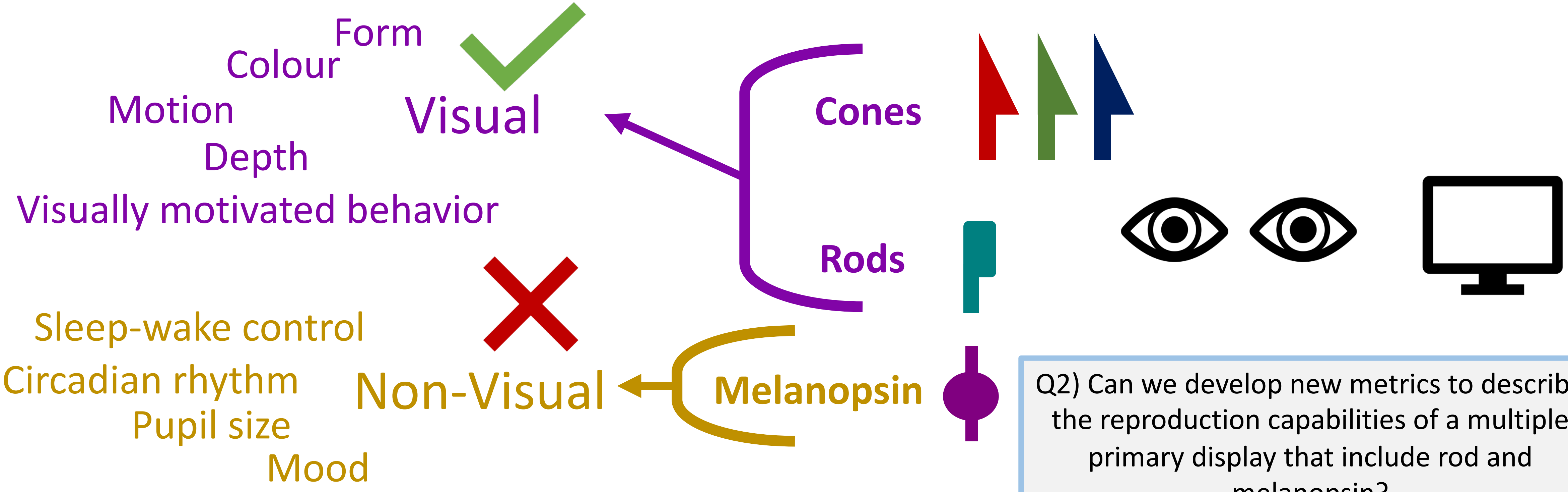
Sleep-wake control
Circadian rhythm
Pupil size
Mood

Non-Visual

Melanopsin

Q2) Can we develop new metrics to describe the reproduction capabilities of a multiple primary display that include rod and melanopsin?

What’s reproduced on displays?



Q2) Can we develop new metrics to describe the reproduction capabilities of a multiple primary display that include rod and melanopsin?

Photoreceptor Signal Reproduction Metric

Outline

- What are we trying to (and what are we actually able to) reproduce with displays?
- **The RealVision MPHDR**
- Metrics for evaluating future display technology

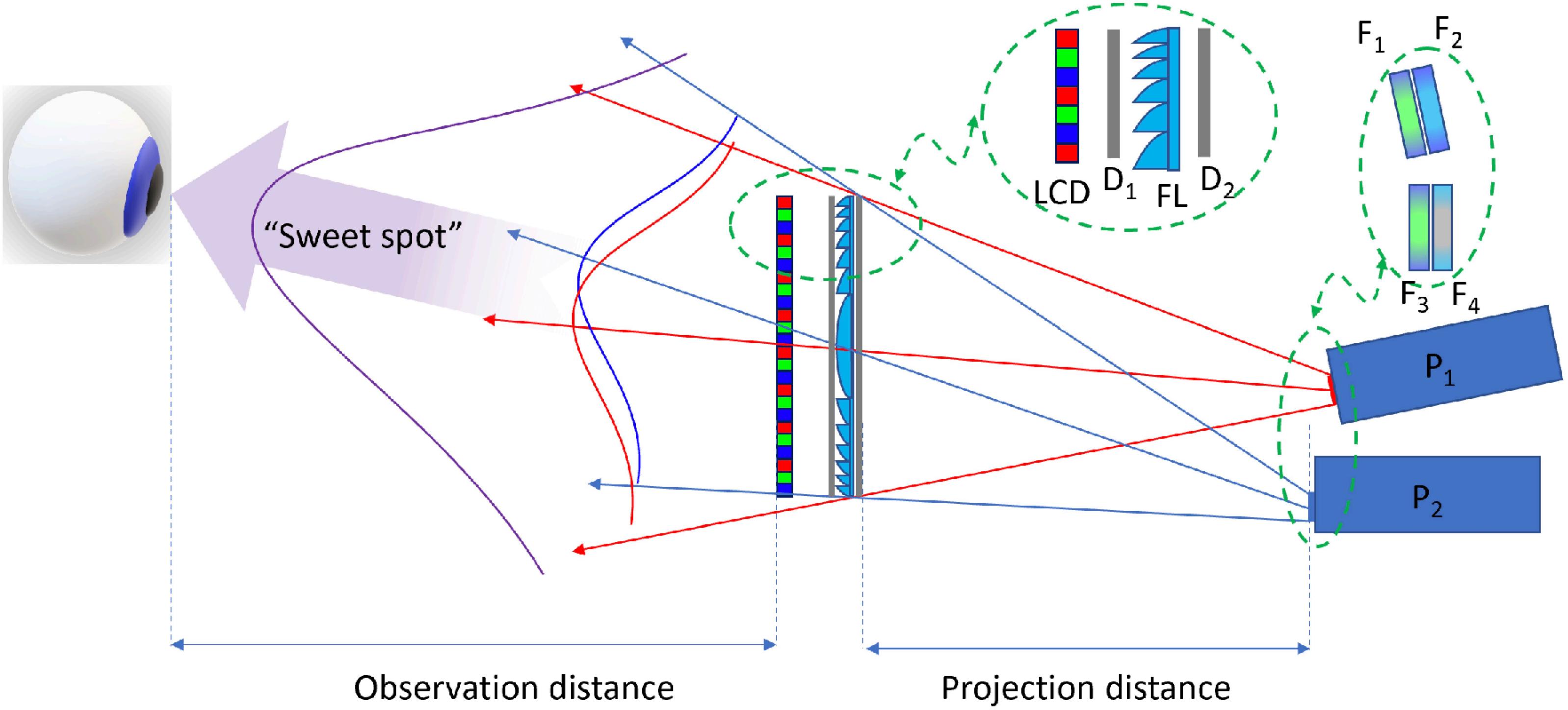
Hexley et al., JOSA A, 2020

One of a Kind

Display	High dynamic range	Spatio-temporal control	>3 primaries
CRT monitors	✘	✓	✘
LCD monitors	✘	✓	✘
HDR displays	✓	✓	✘
Multi-primary Maxwellian view systems	✓	✘	✓
Multi-primary projector based displays	✘	✓	✓
The RealVision MPHDR	✓	✓	✓

Hexley et al., JOSA A, 2020

Design



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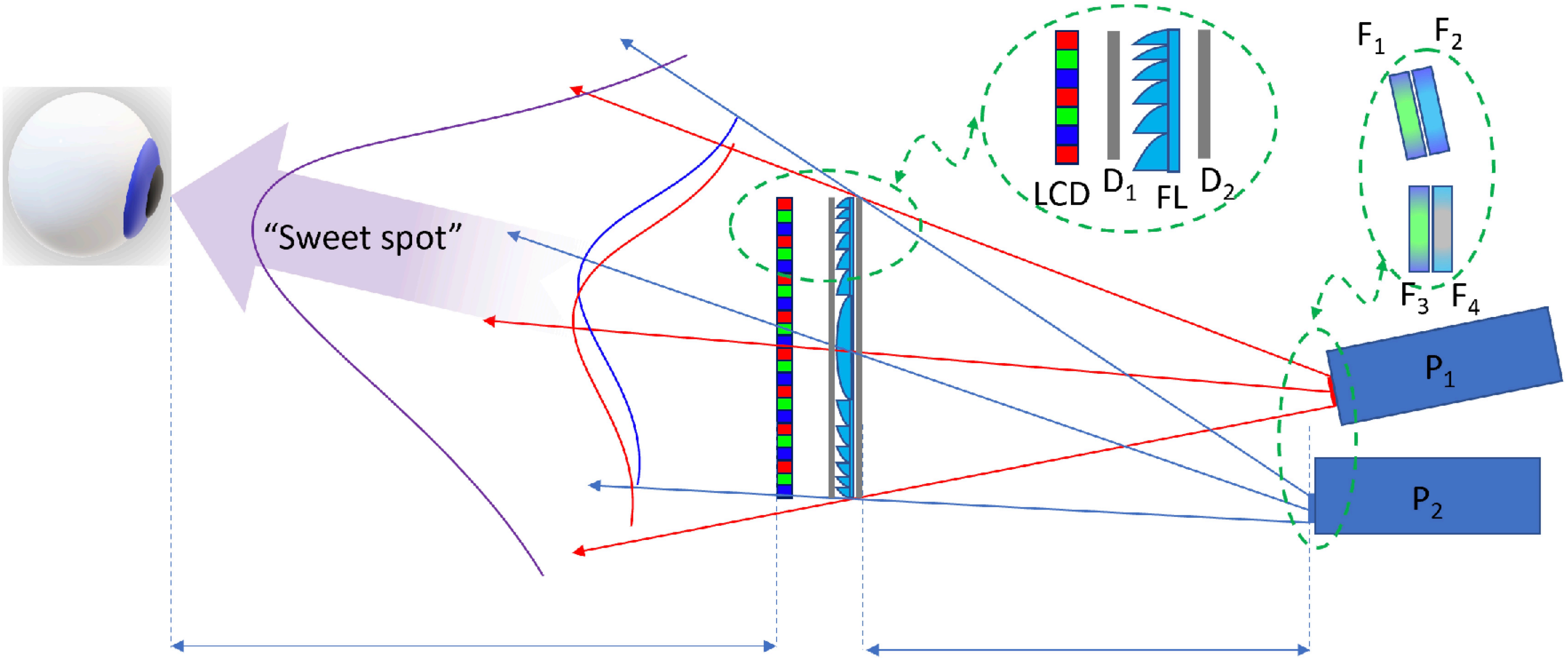

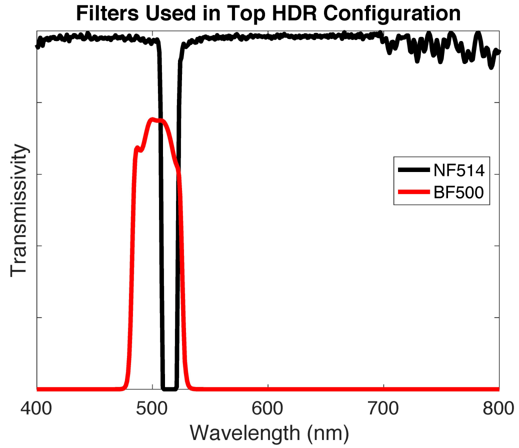

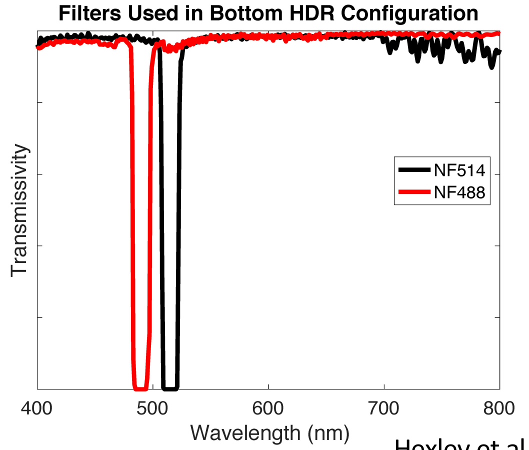

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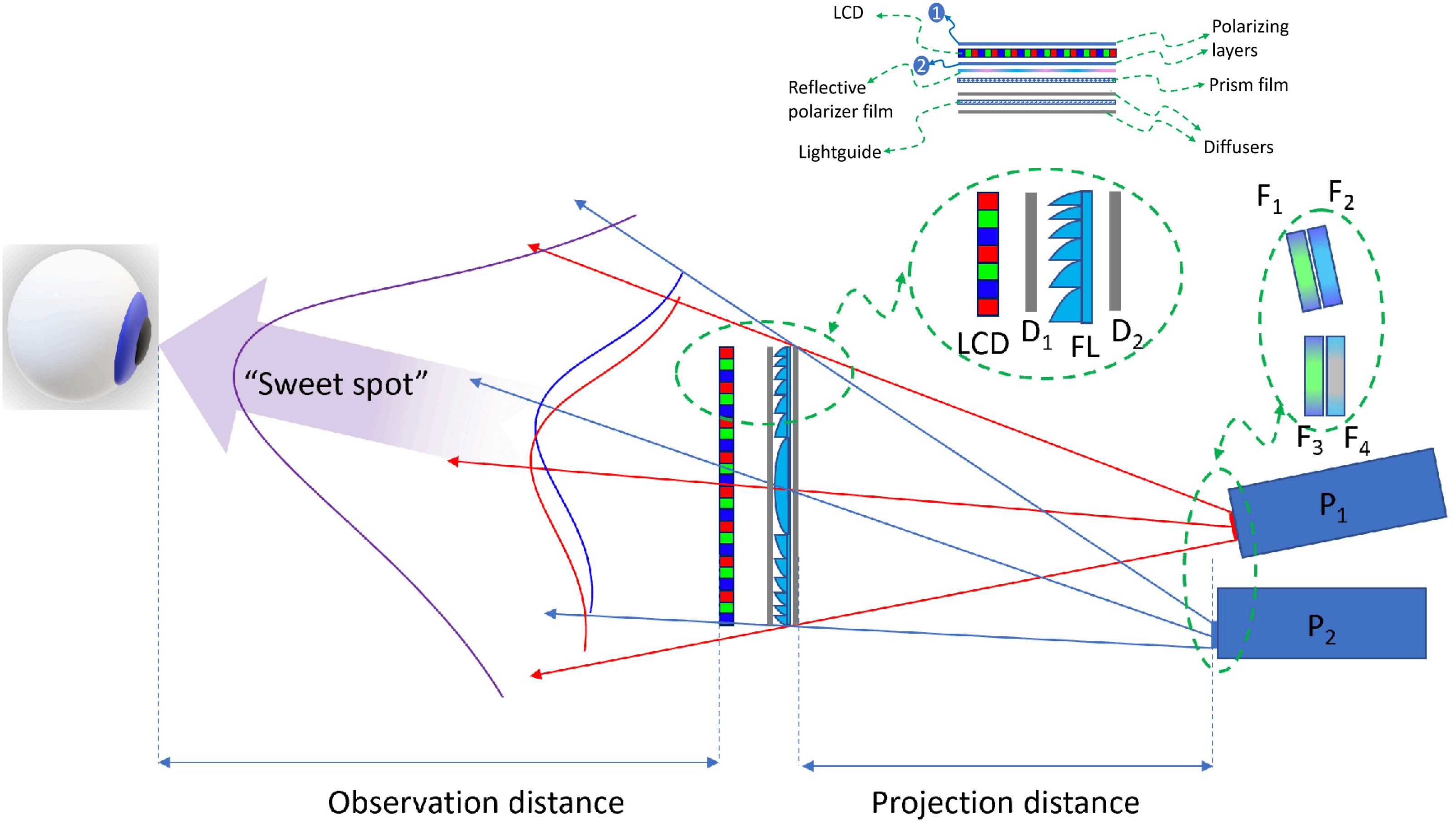

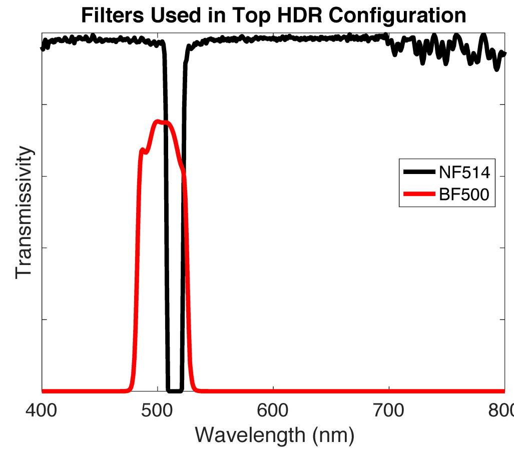

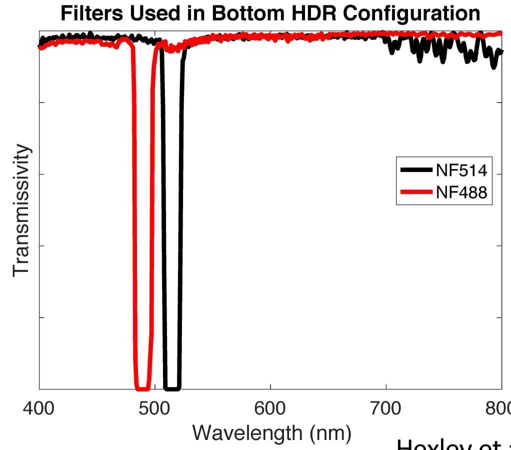

Hexley et al., JOSA A, 2020

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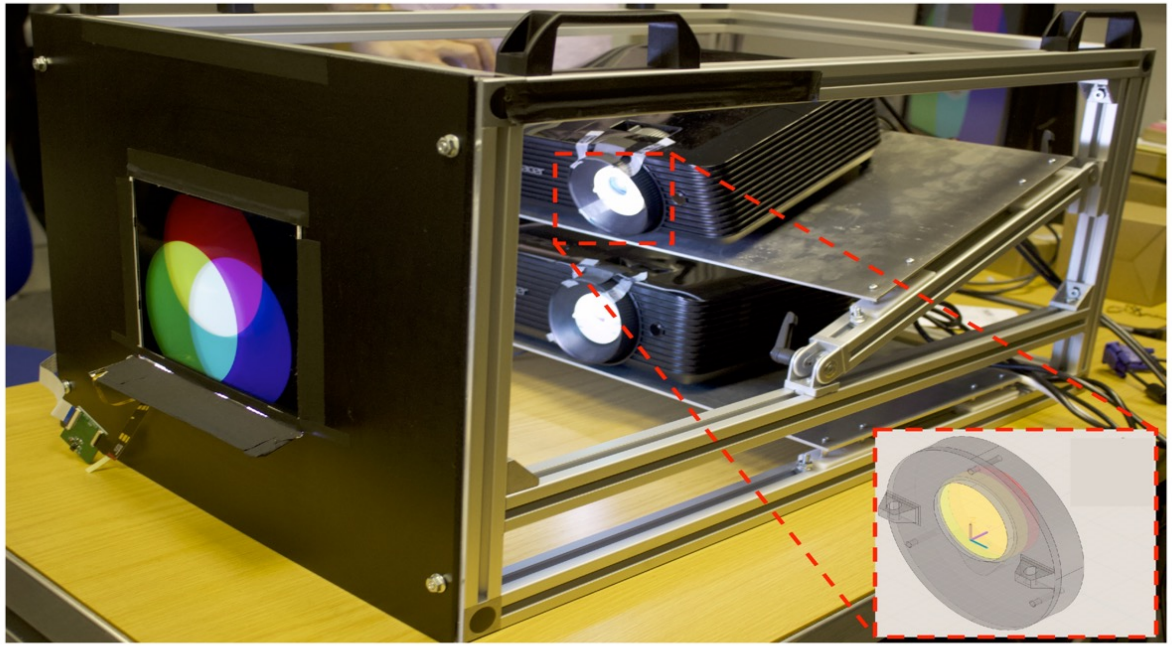
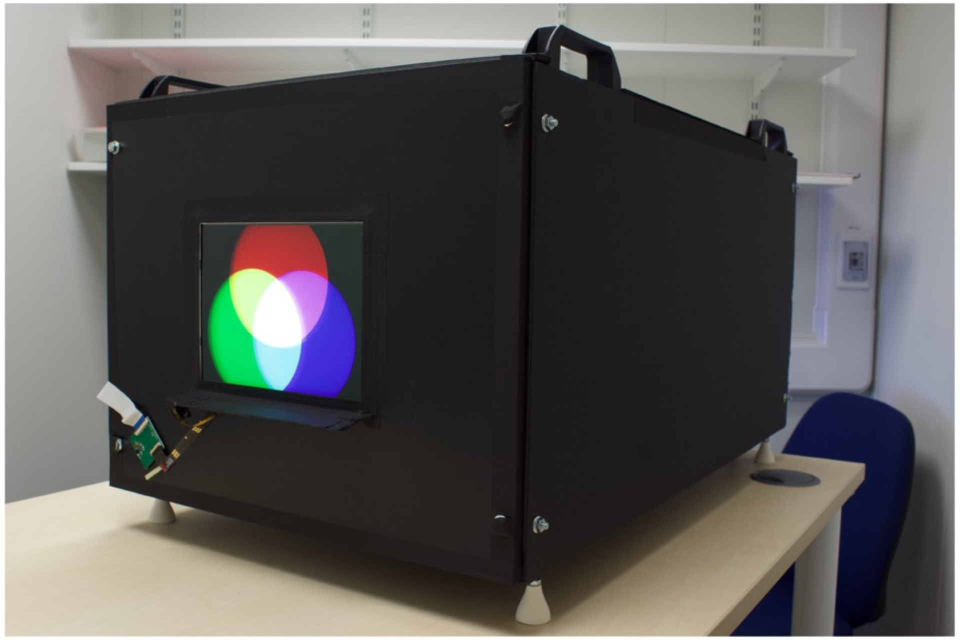
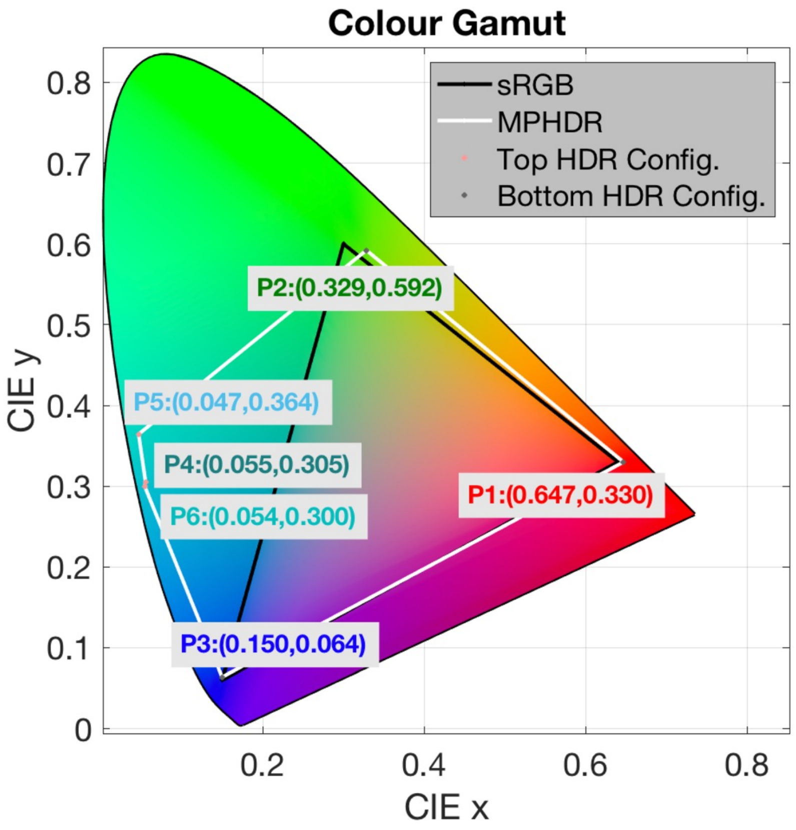
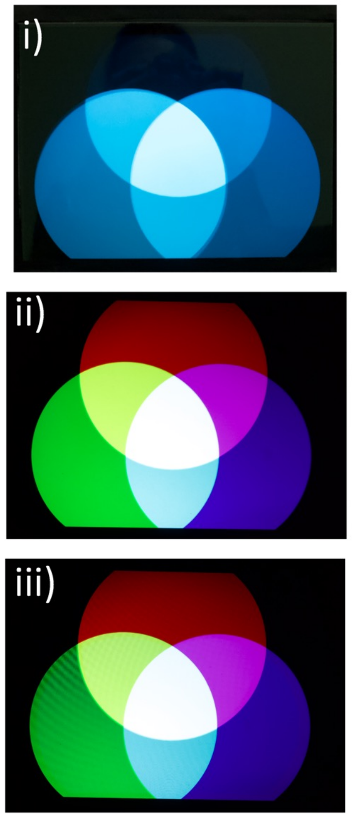




Hexley et al., JOSA A, 2020

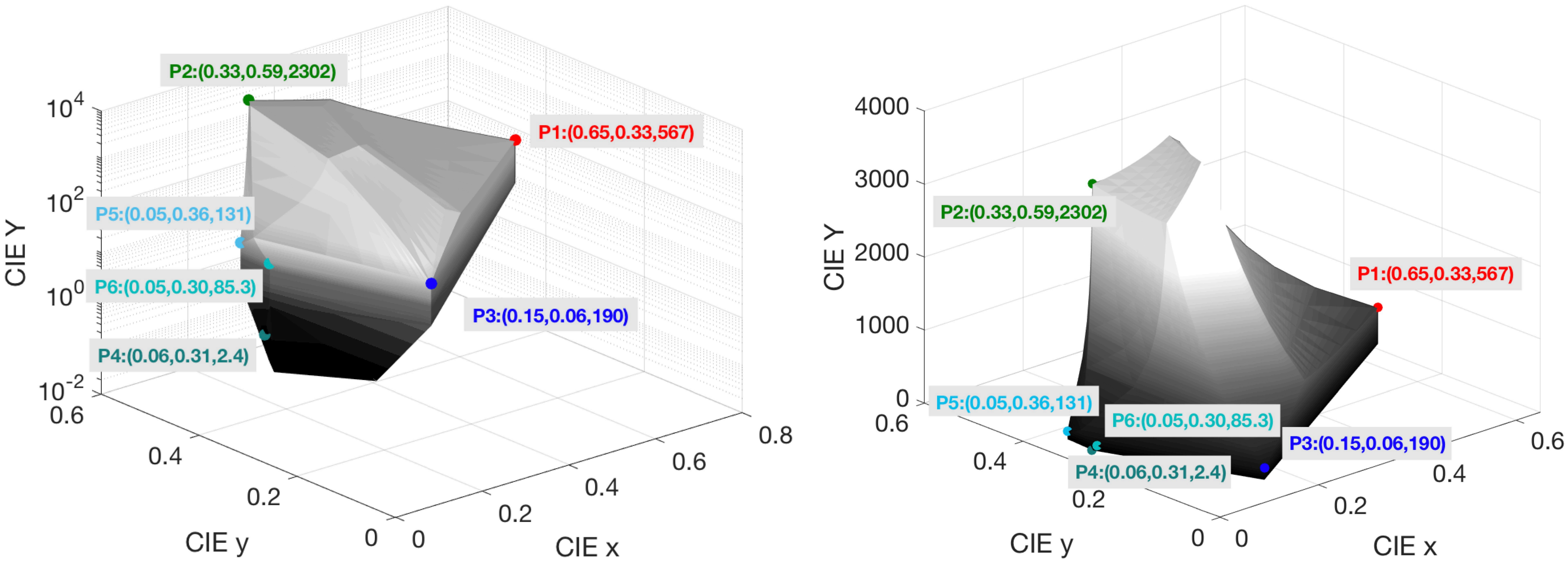
Colour Gamut





Hexley et al., JOSA A, 2020

3D Colour Gamut



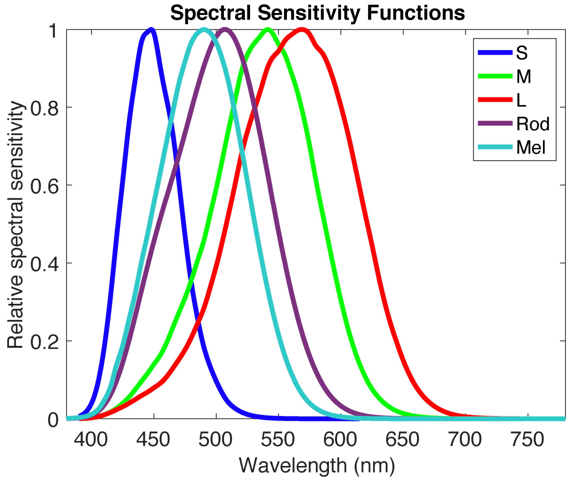
Hexley et al., JOSA A, 2020

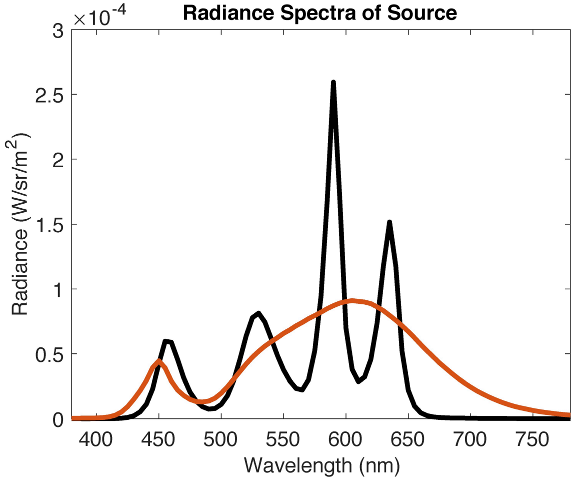
Dynamic Range

Display	Full On/Off (Global) Contrast	ANSI (Local) Contrast
LCD panel	1140:1	725:1
Top DLP	3430:1	100:1
Bottom DLP	2810:1	594:1
Top HDR configuration	3,930,000:1	72,400:1
Bottom HDR configuration	3,220,000:1	431,000:1
MPHDR	3,240,000:1	341,000:1

Hexley et al., JOSA A, 2020

Melanopsin Isolation





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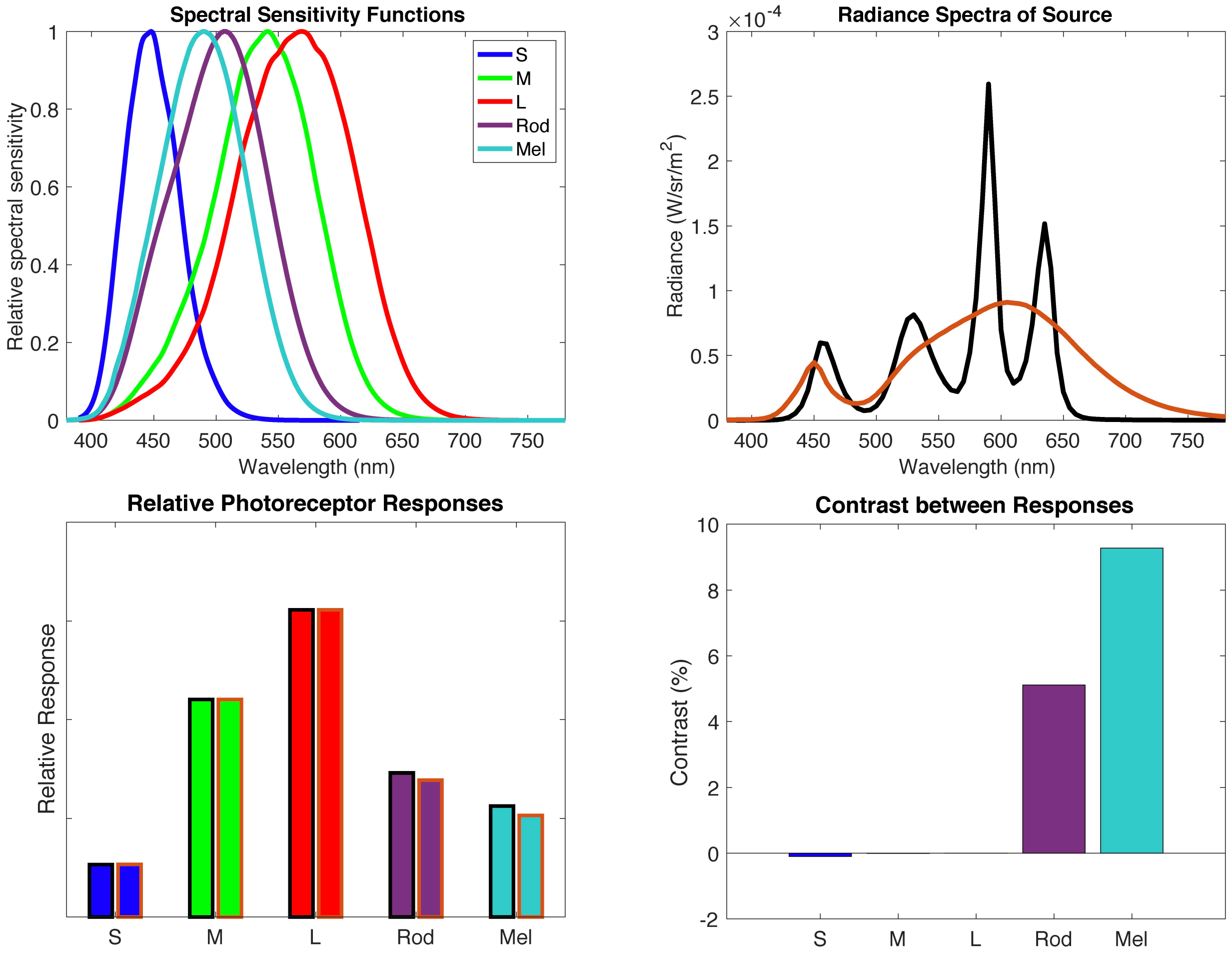
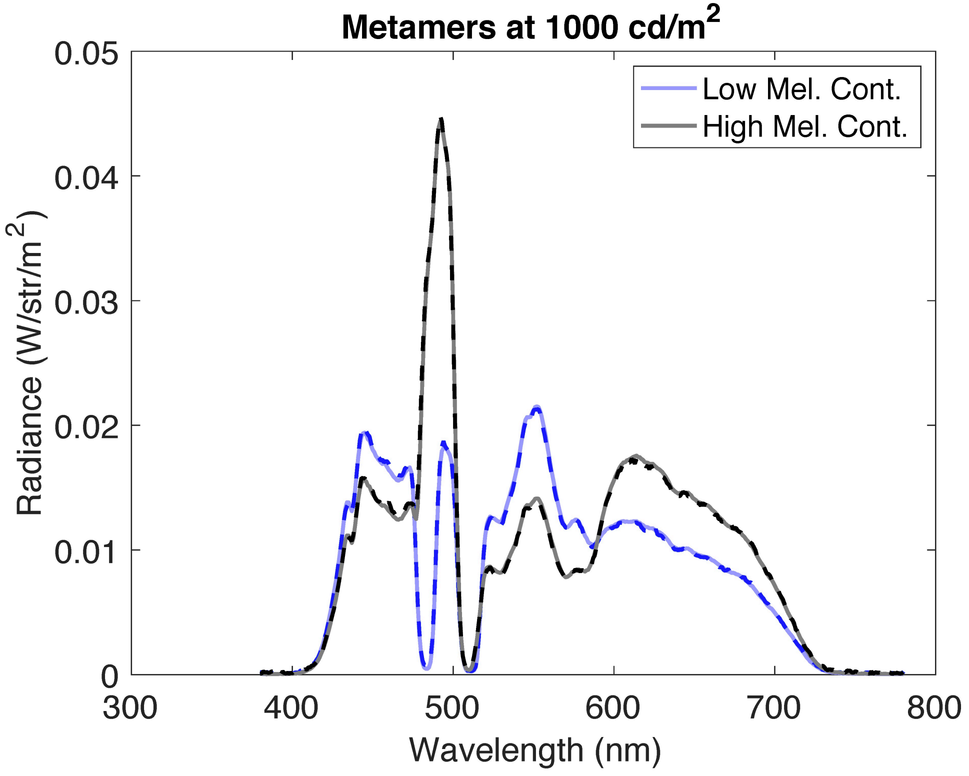
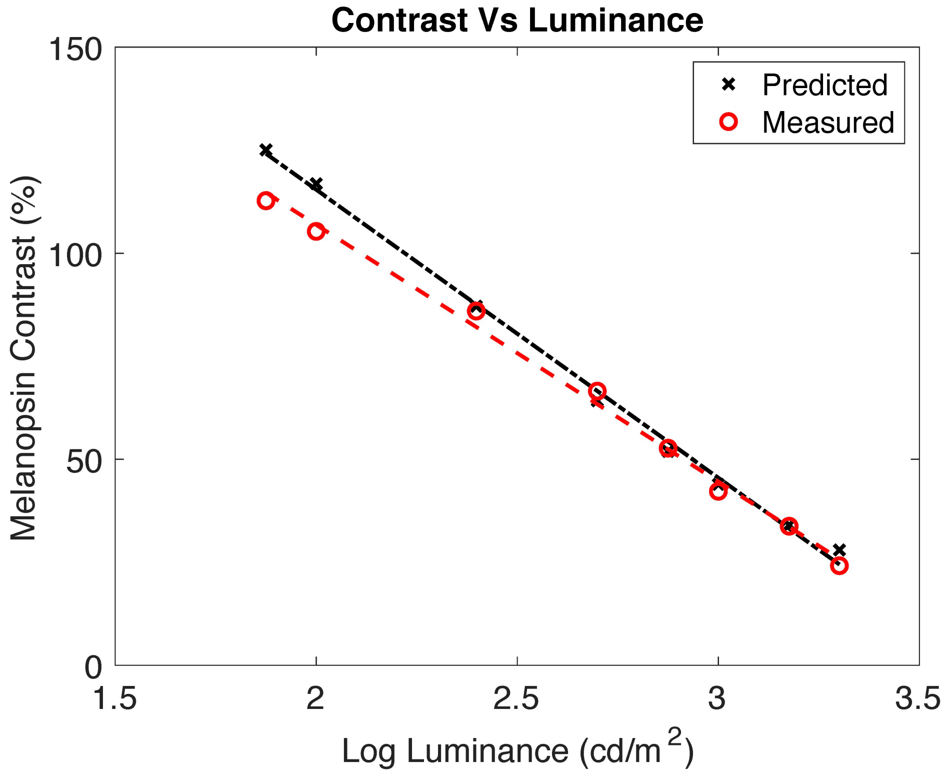


Hexley et al., JOSA A, 2020

Melanopic Contrast





Hexley et al., JOSA A, 2020

Next Steps

- Melanopsin (and rod/cone) isolating experiments with high dynamic range, spatiotemporal control
    - E.g. Pupillary light reflex across luminance levels with high/low melanopic contrast

Hexley et al., JOSA A, 2020

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- Moving towards a fully independent six primary system

Hexley et al., JOSA A, 2020

Next Steps

- Melanopsin (and rod/cone) isolating experiments with high dynamic range, spatiotemporal control
  - E.g. Pupillary light reflex across luminance levels with high/low melanopic contrast
- Moving towards a fully independent six primary system
- Quicker methods for spatial spectral calibration

Hexley et al., JOSA A, 2020

Outline

- What are we trying to (and what are we actually able to) reproduce with displays?
- The RealVision MPHDR
- **Metrics for evaluating future display technology**

Beyond Colour Gamuts

- What's the equivalent of the CIExy horseshoe diagram in 5D photoreceptor space?

Beyond Colour Gamuts

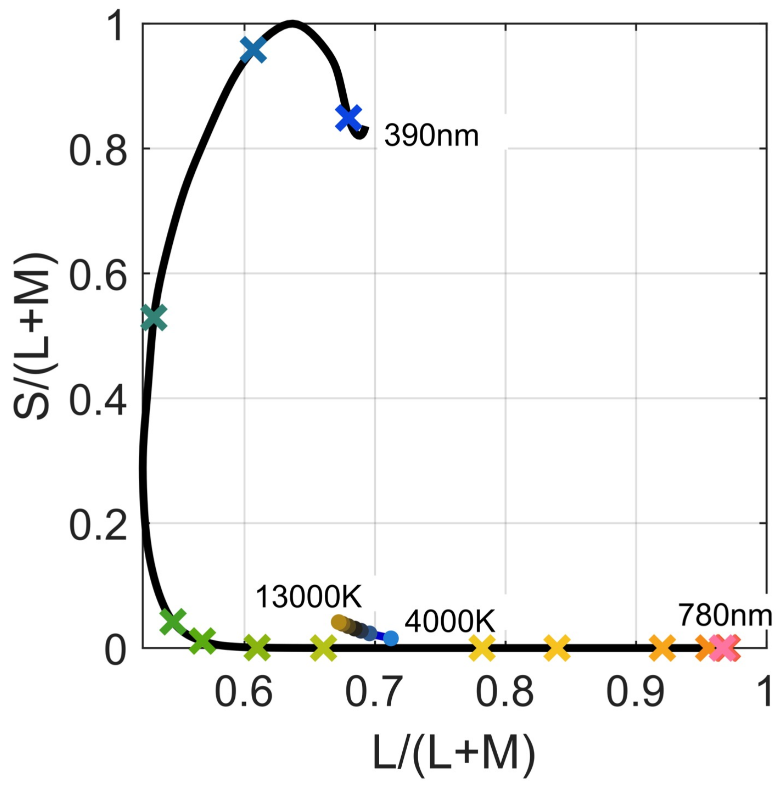
- What's the equivalent of the CIExy horseshoe diagram in 5D photoreceptor space?
- Our approach:

1) use photoreceptor-based chromaticity diagrams, which allow for a natural extension to include melanopsin

2) use a real-world dataset as a reference to quantify reproduction against

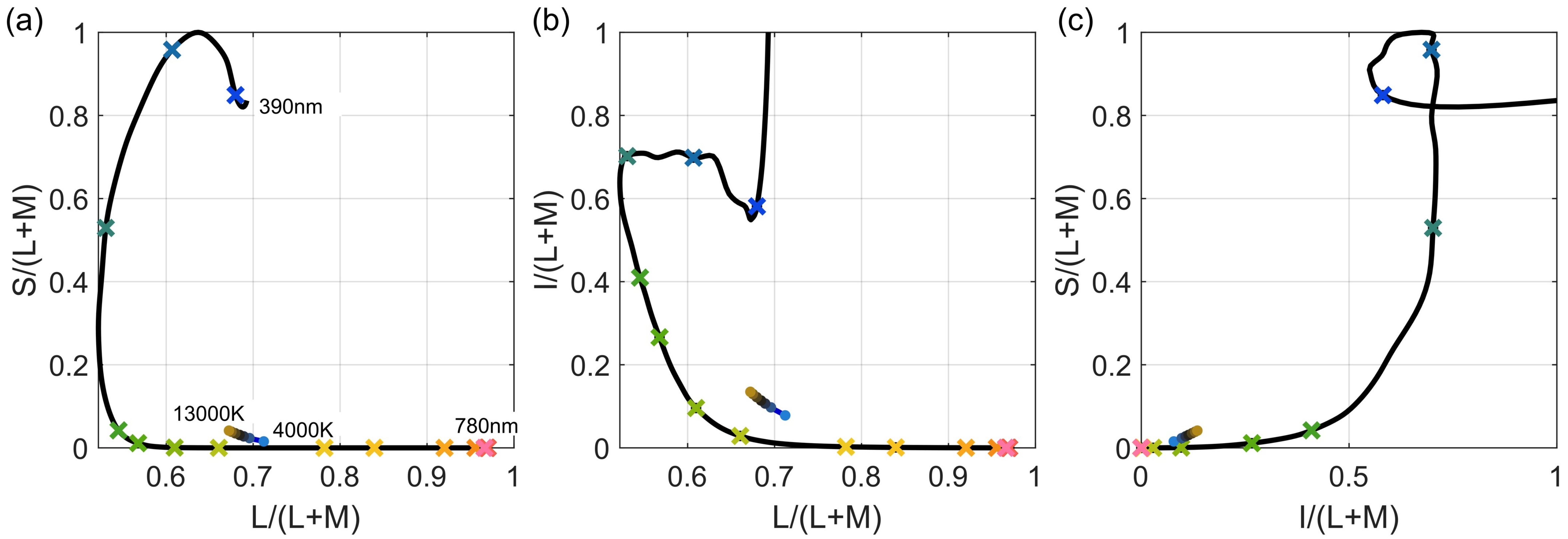
Hexley et al., BioRxiv, 2021

Photoreceptor Based Chromaticity Diagrams



MacLeod & Boynton, 1979
Hexley et al., BioRxiv, 2021

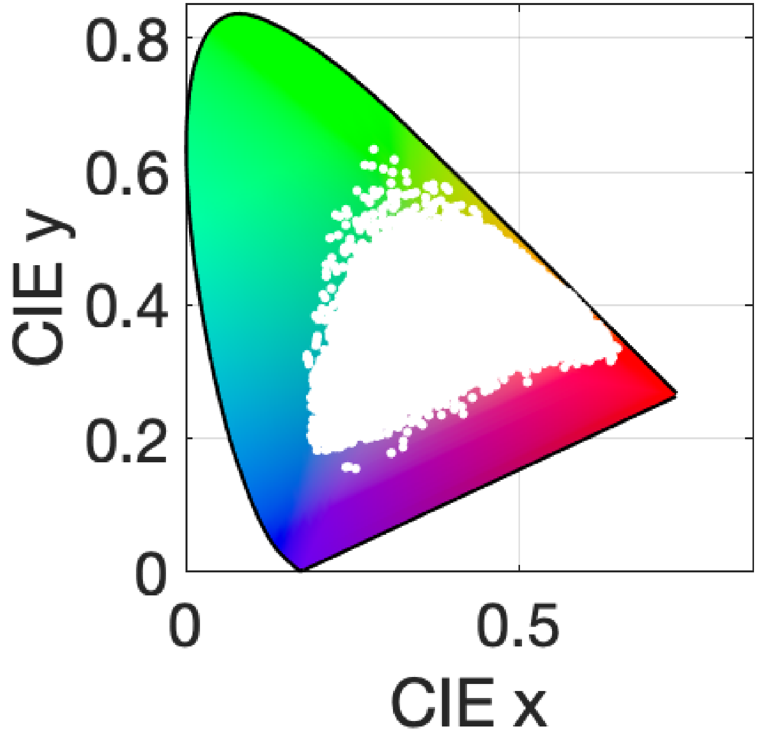
Photoreceptor Based Chromaticity Diagrams



Hexley et al., BioRxiv, 2021

Real-World Reference Dataset

401 illuminants; 99 surface reflectances



Houser et al., 2013; ITU, 2015
Hexley et al., BioRxiv, 2021

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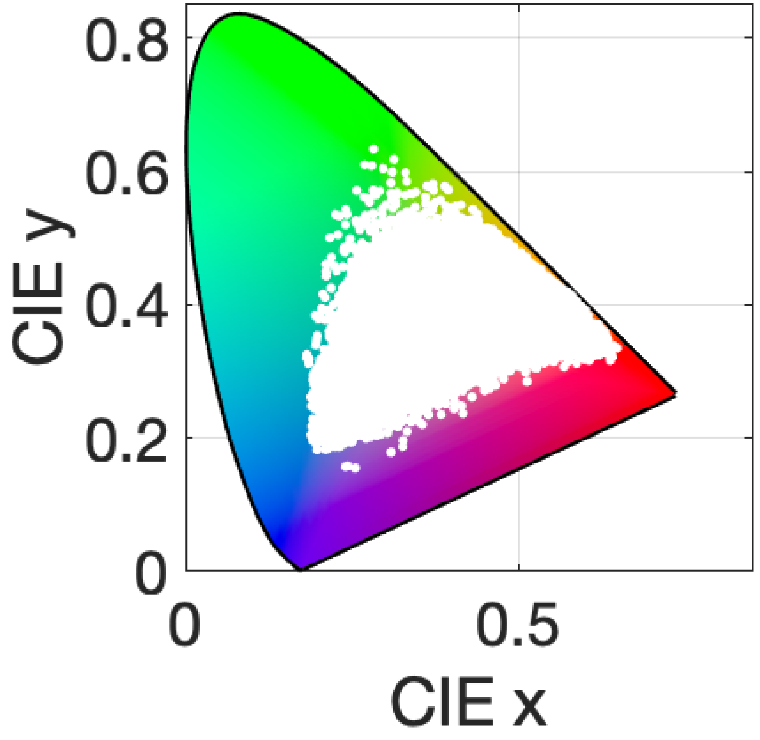
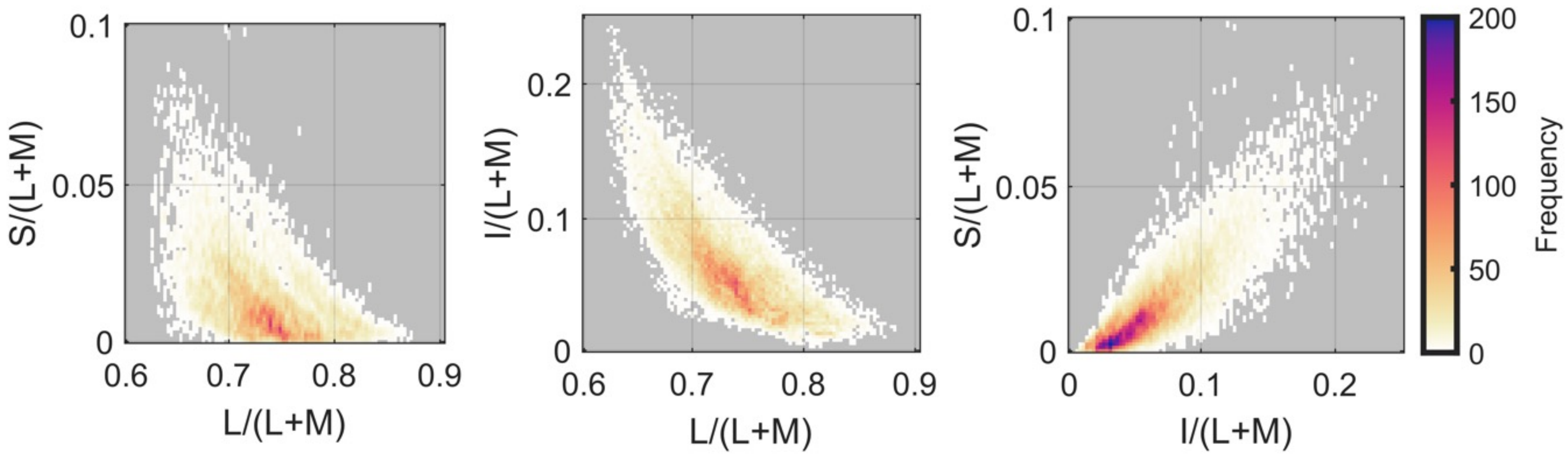
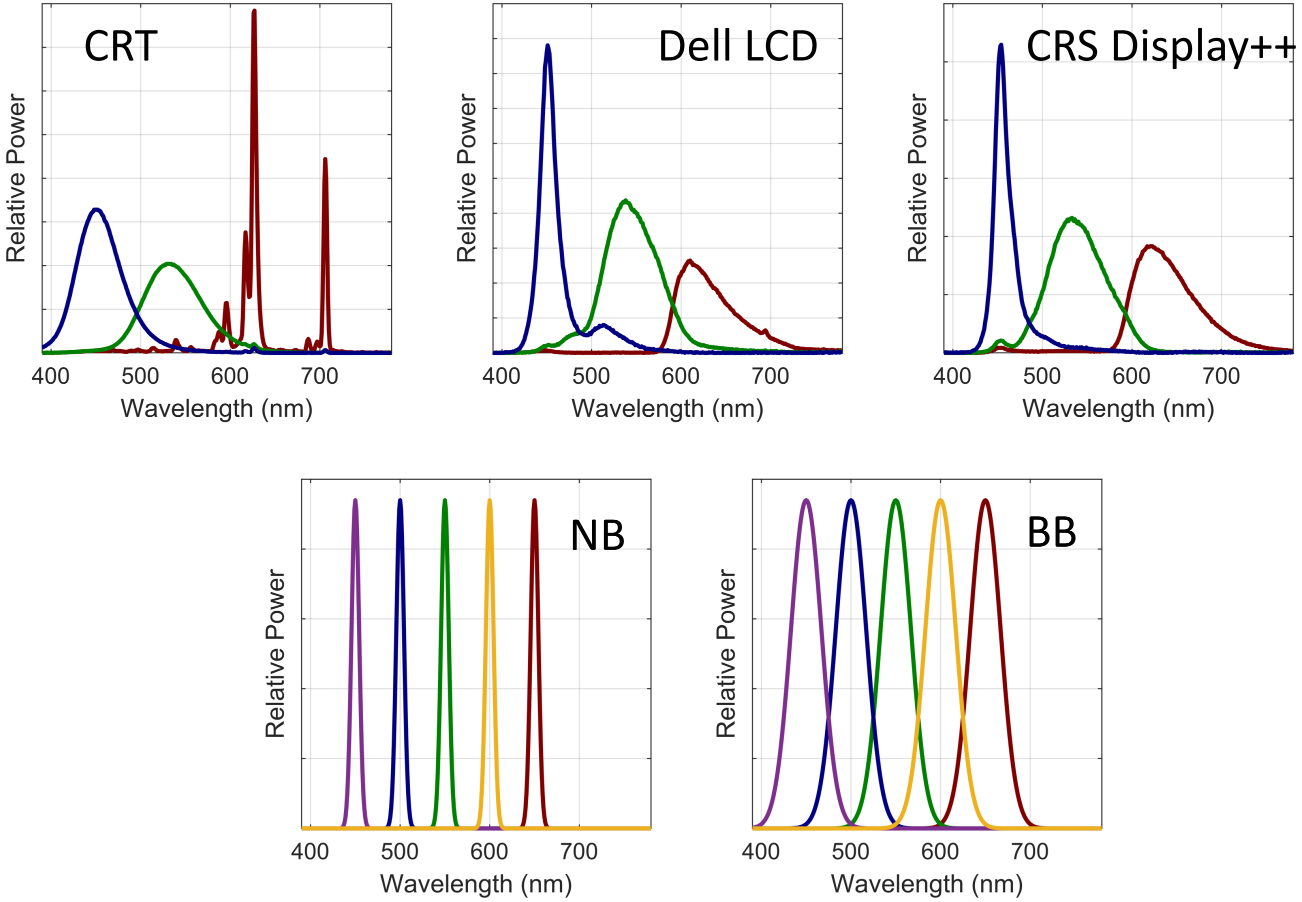




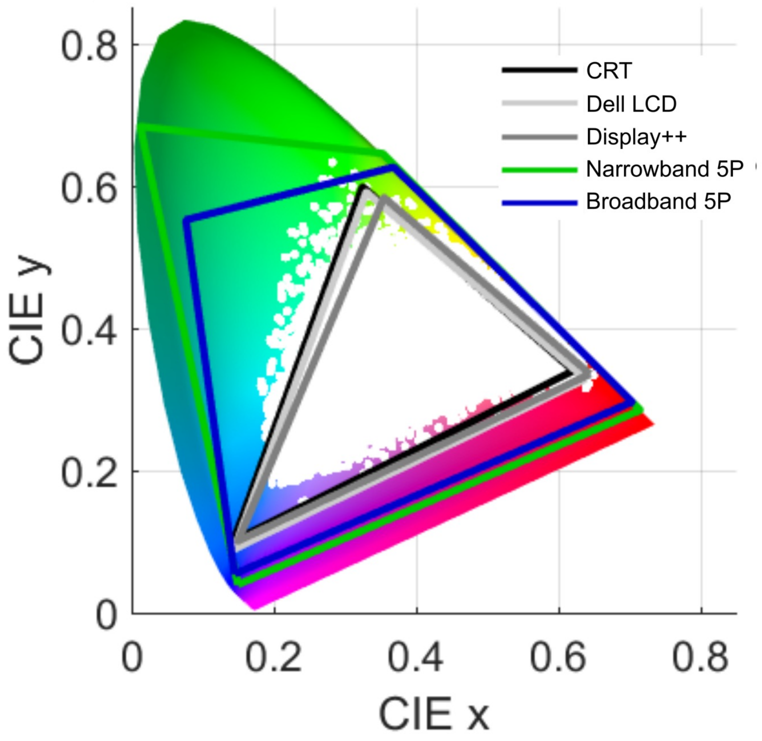
Hexley et al., BioRxiv, 2021

Evaluating Some Example Displays



Hexley et al., BioRxiv, 2021

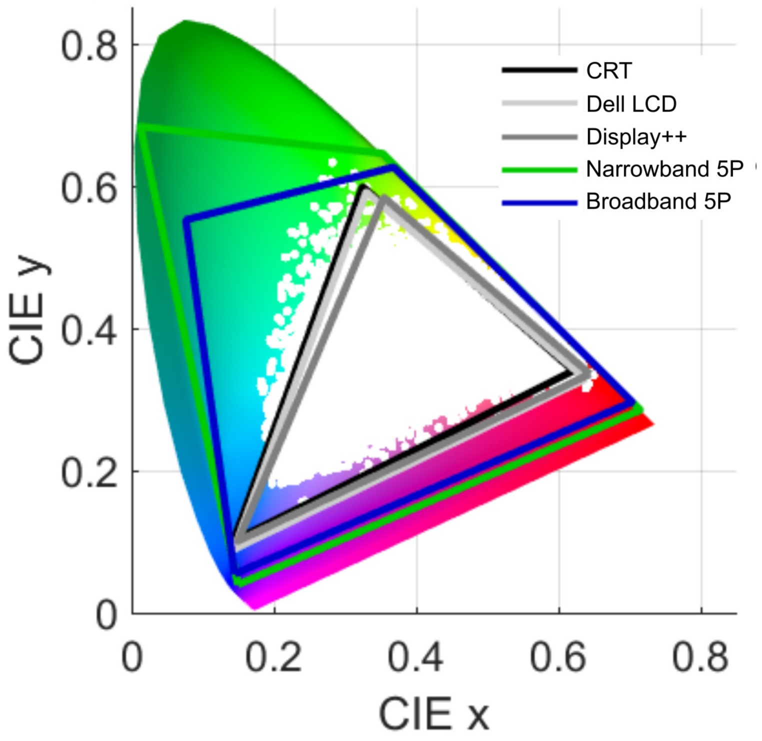
Colour Reproduction

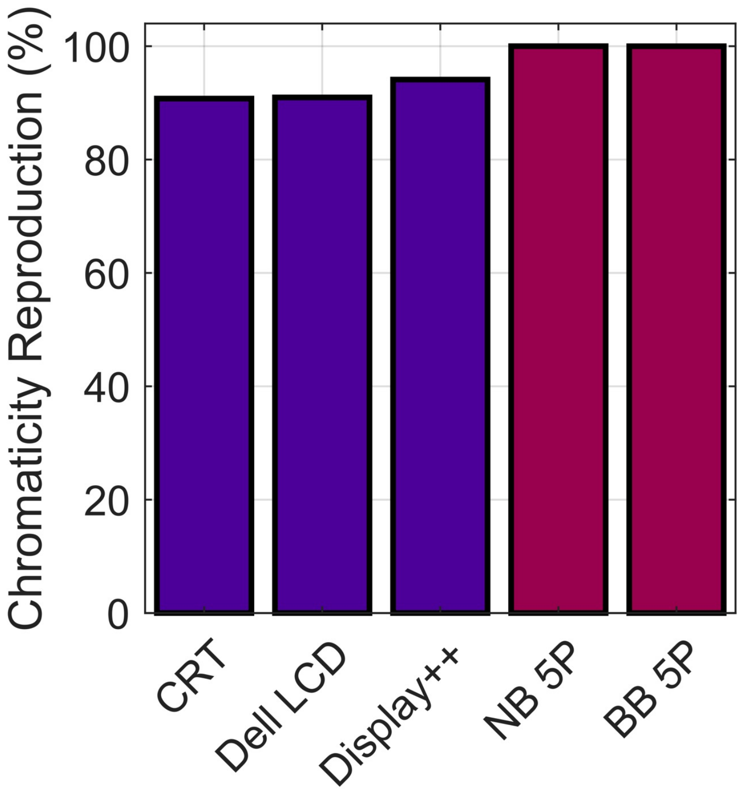


$$Chromaticity\ Reproduction = \frac{No. of\ spectra\ within\ gamut}{Total\ no. spectra}$$

Hexley et al., BioRxiv, 2021

Colour Reproduction





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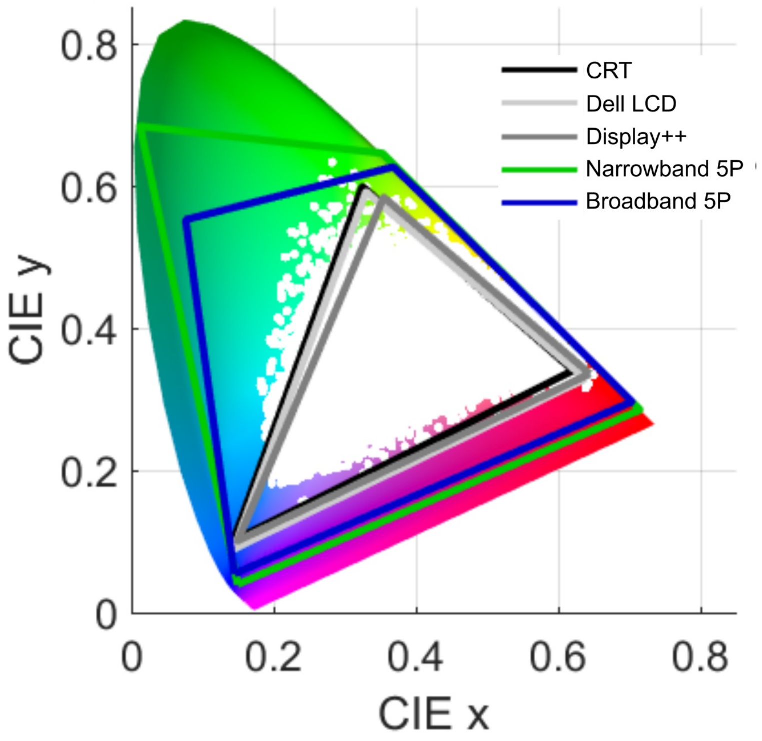
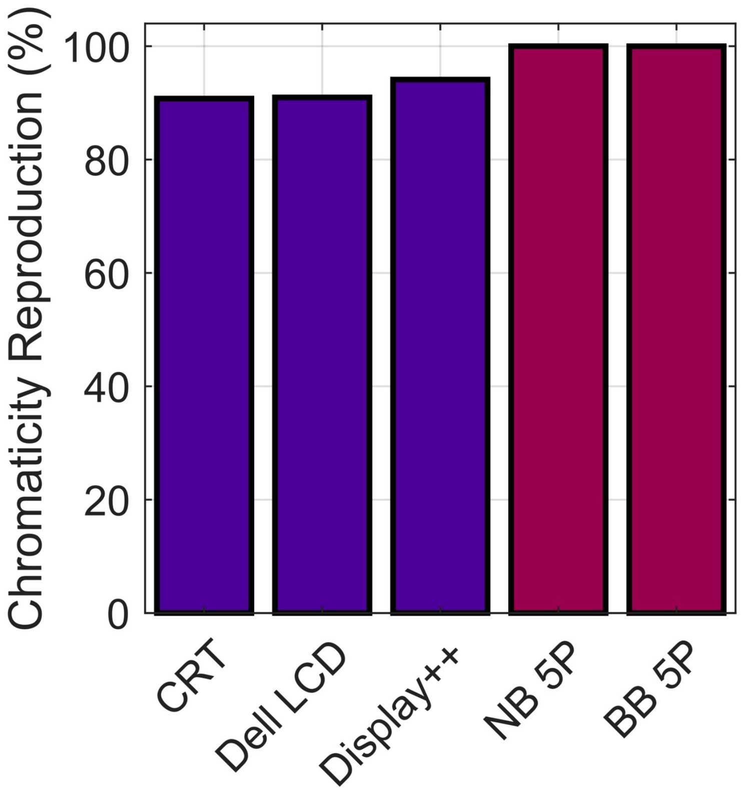
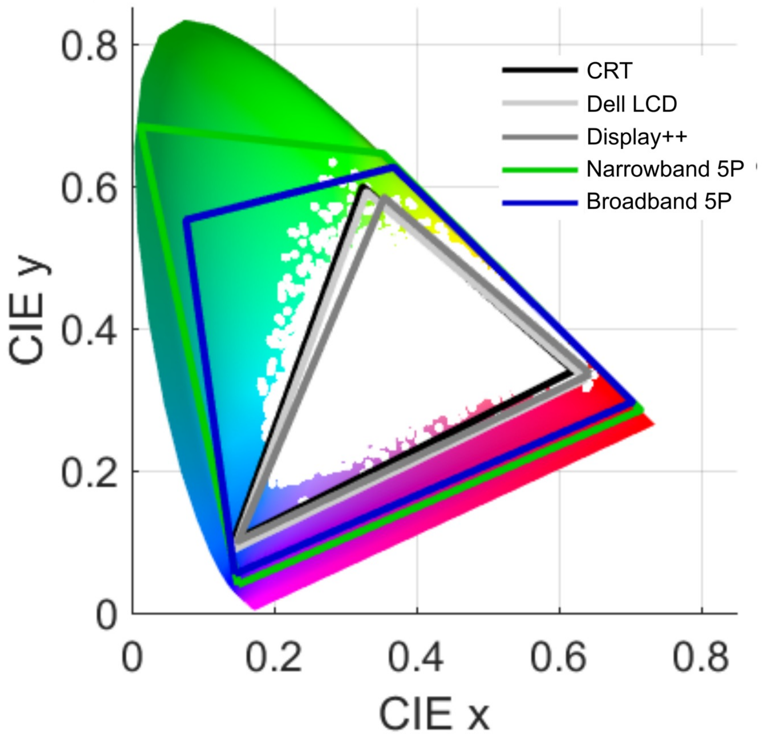


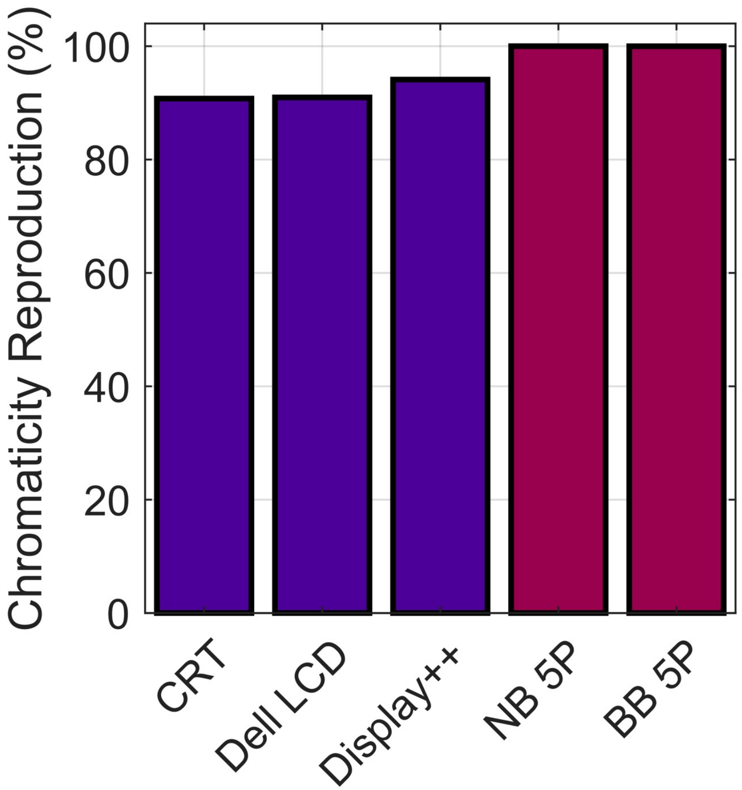


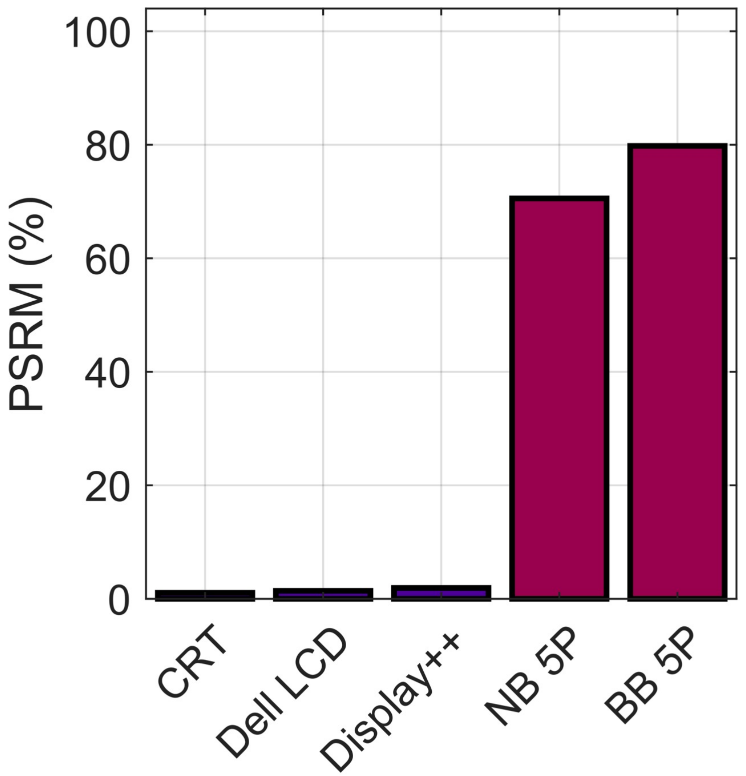
$$PSRM = \frac{No. of\ spectra\ within\ gamut}{Total\ no. spectra}$$

Hexley et al., BioRxiv, 2021

Photoreceptor Signal Reproduction

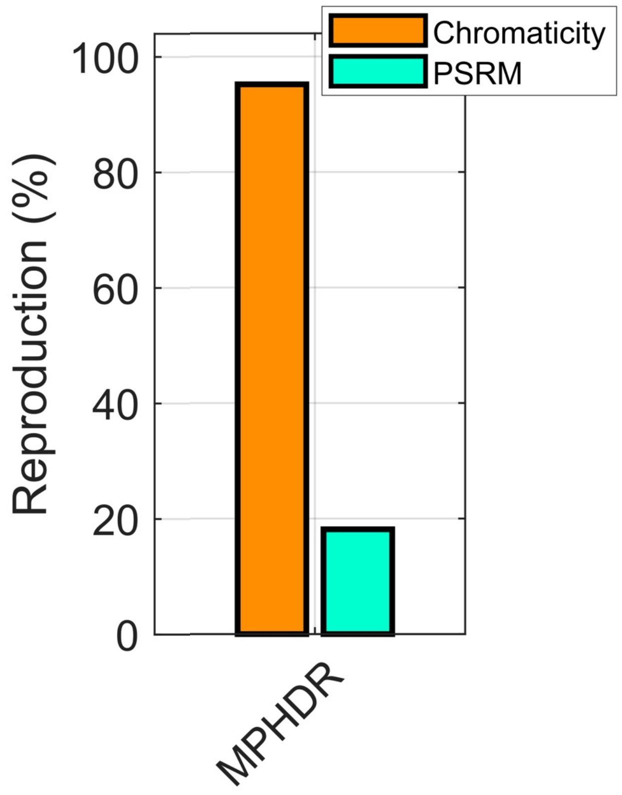


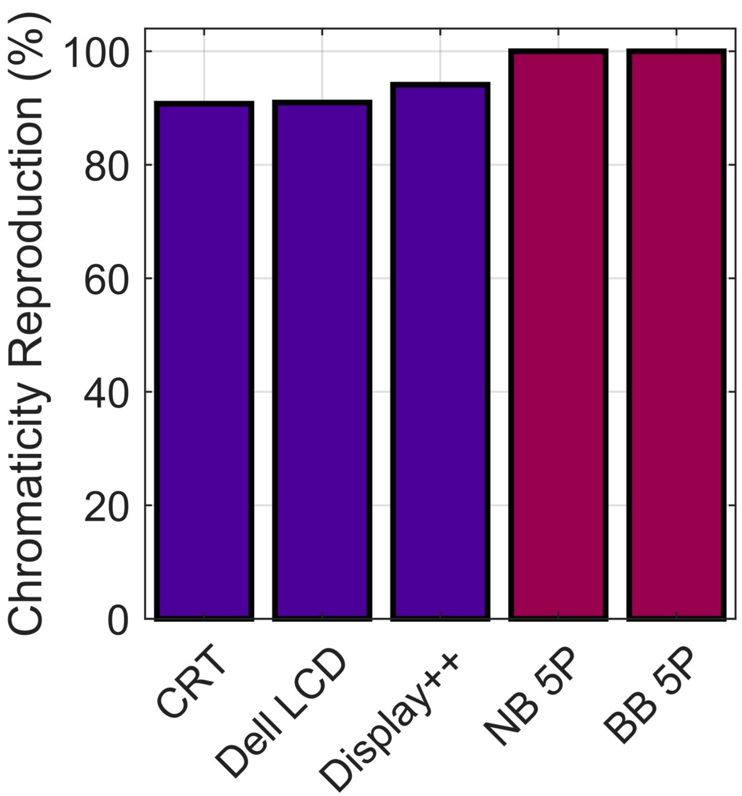


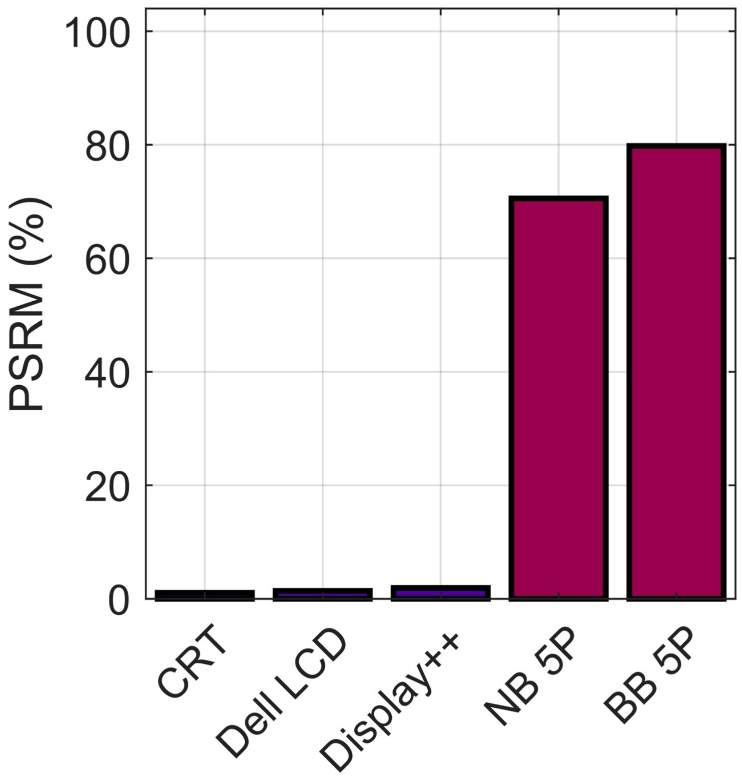


Hexley et al., BioRxiv, 2021

Photoreceptor Signal Reproduction

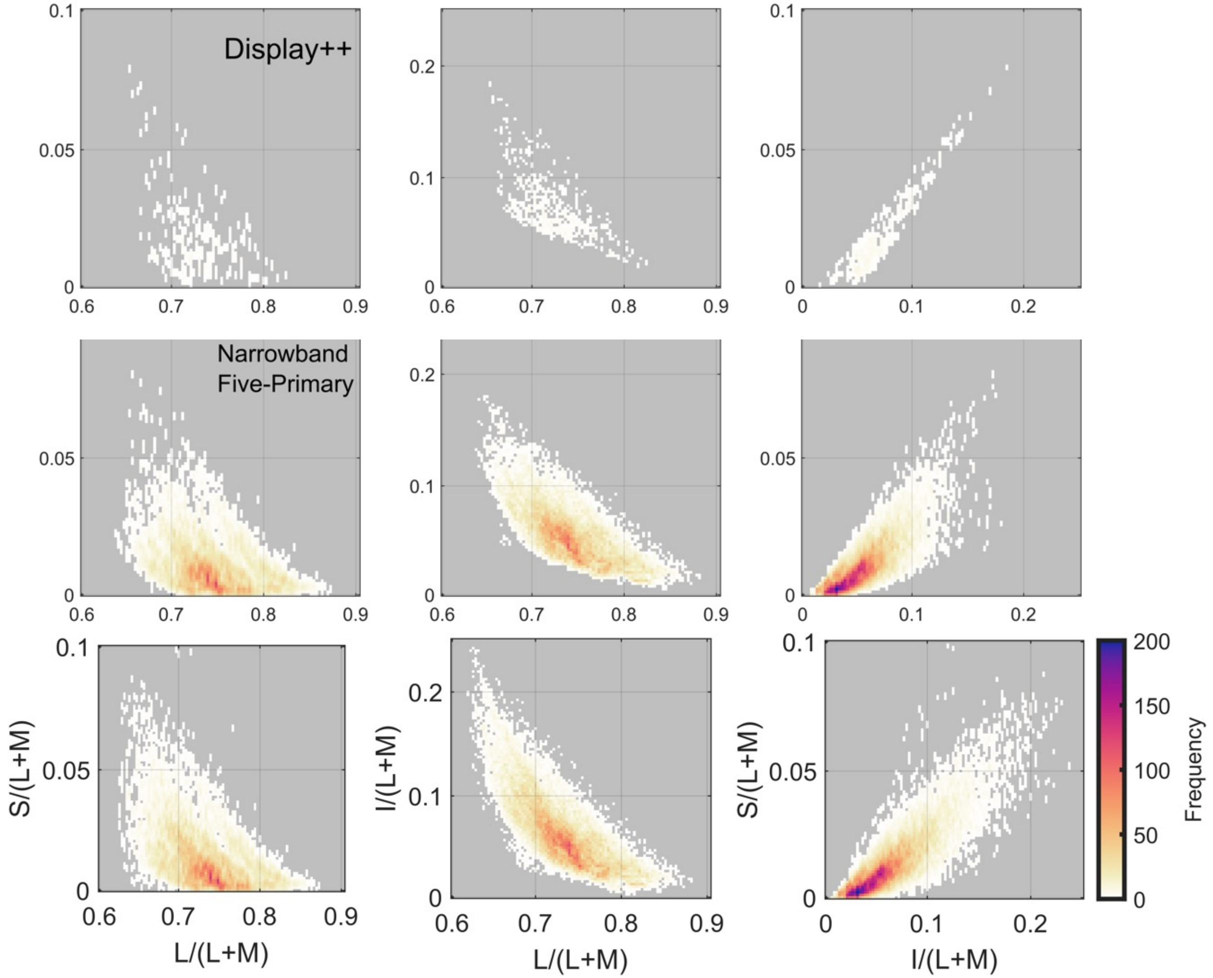






Hexley et al., BioRxiv, 2021

Photoreceptor Signal Reproduction



Hexley et al., BioRxiv, 2021

Next Steps

- Quantify “spectral diet” of human observers

Next Steps

- Quantify "spectral diet" of human observers
- Optimization of primary selection in multiple primary displays

Next Steps

- Quantify “spectral diet” of human observers
- Optimization of primary selection in multiple primary displays
- Move from photoreceptor reproduction to “perceptual” metrics

Outline

- What are we trying to (and what are we actually able to) reproduce with displays?
- The RealVision MPHDR
- Metrics for evaluating future display technology

Acknowledgements

Co-Authors:

Prof Hannah Smithson
Dr Rafal Mantiuk
Dr Manuel Spitschan
Dr Takuma Morimoto
Dr Ali Özgür Yöntem

Funding:

MARIE CURIE ACTIONS

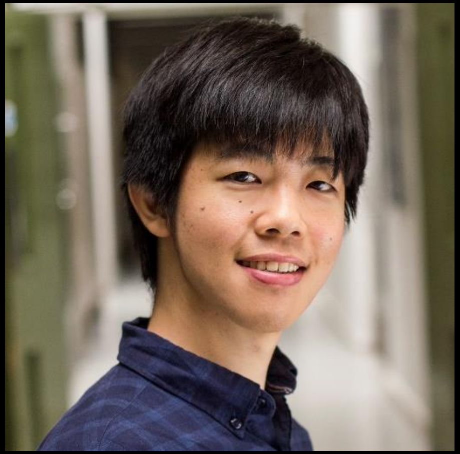
realVision

Oxford Perception Lab

OSA The Optical Society

Novel Displays for Future Vision Science

A multimodal volumetric display using acoustic holography



Ryuji Hirayama
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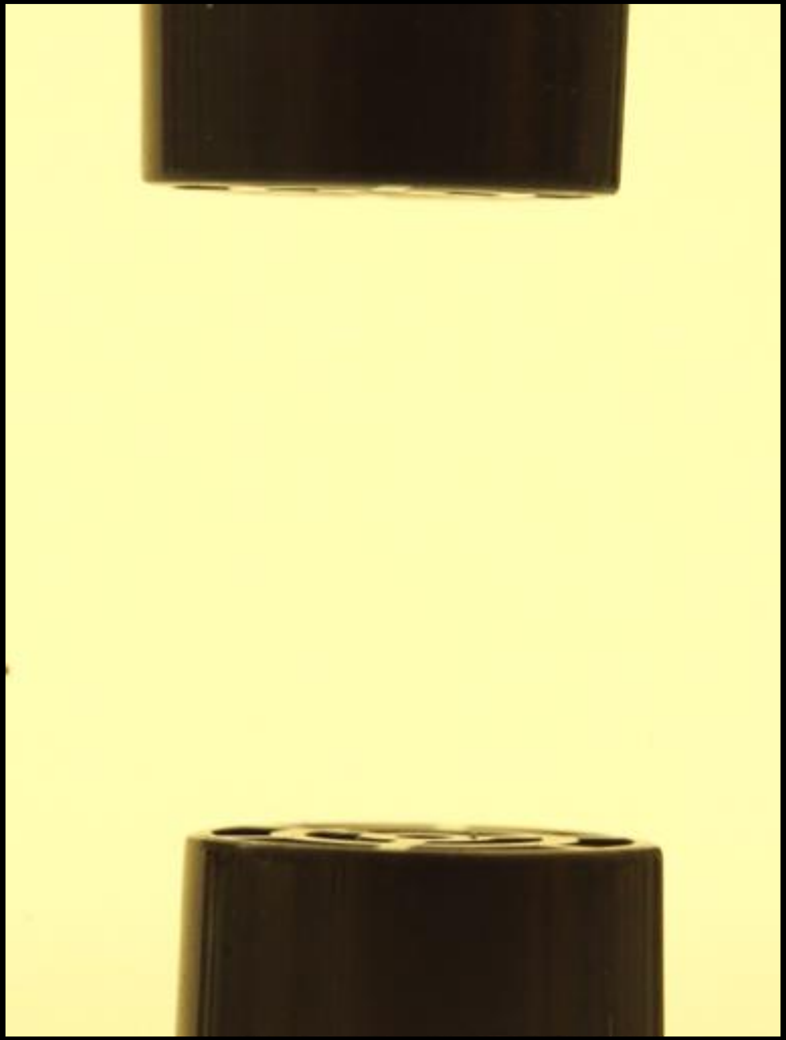
Introduction

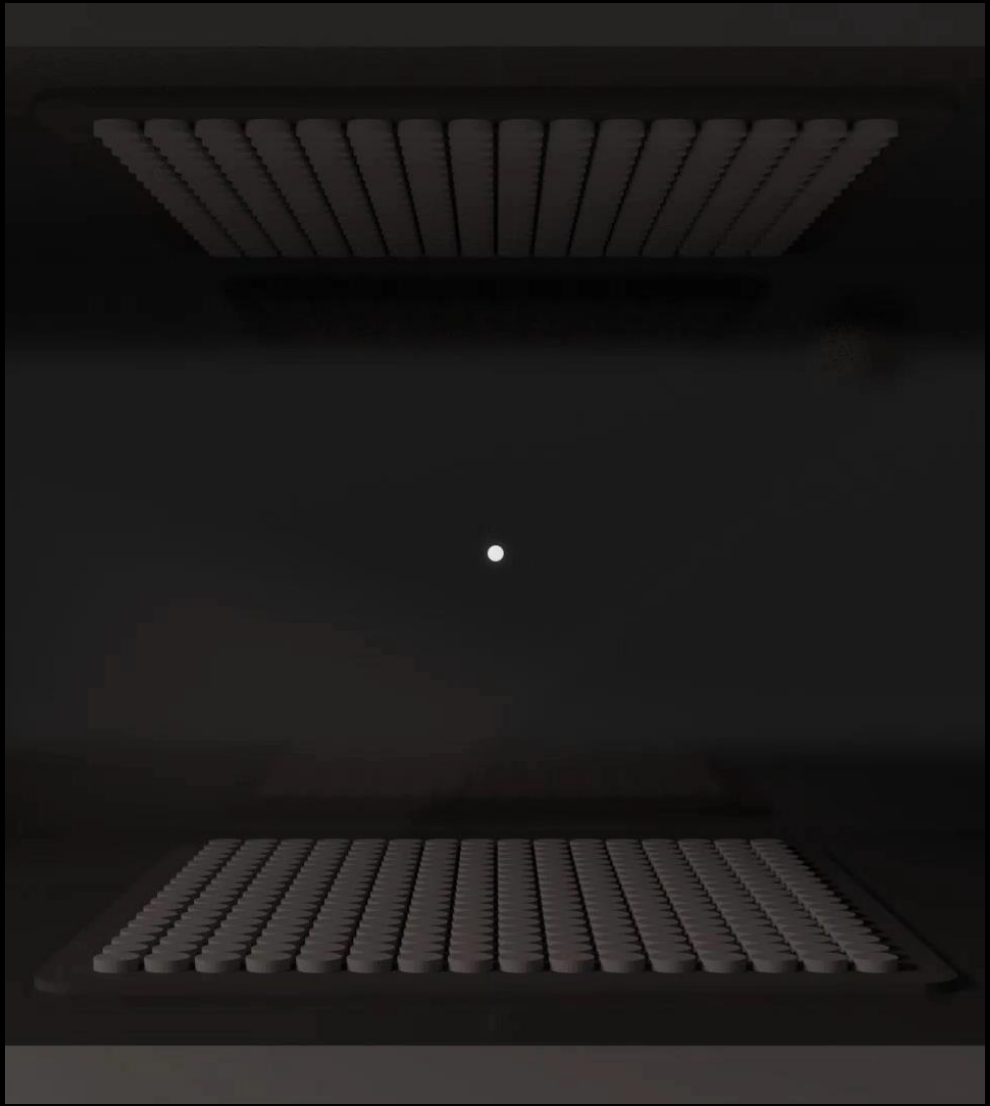
Acoustic Levitation

1 cm



- Particles are trapped at nodes of a standing wave
- Particles can move up and down but not in other ways

3D manipulation using ultrasound



- 3D manipulation needs arrays of transducers
- Multiple particles can be levitated

Holographic acoustic tweezers

A. Marzo and B. W. Drinkwater, PNAS 116(1), 84-89 (2019)

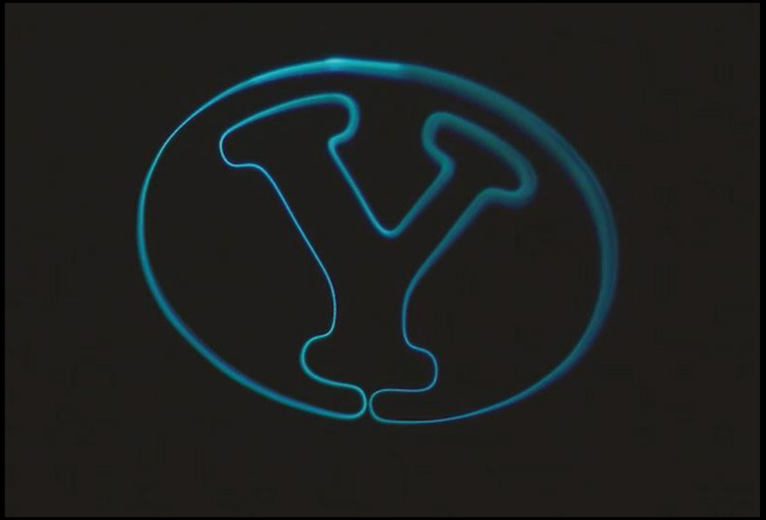
Variety of materials that can be levitated

Water Droplet
(resonant oscillations)

Fake diamond
(Zircon; 3.5mm; 4.7 g/cm^3)

Fabric
(projection mapping)

Particle-based volumetric displays



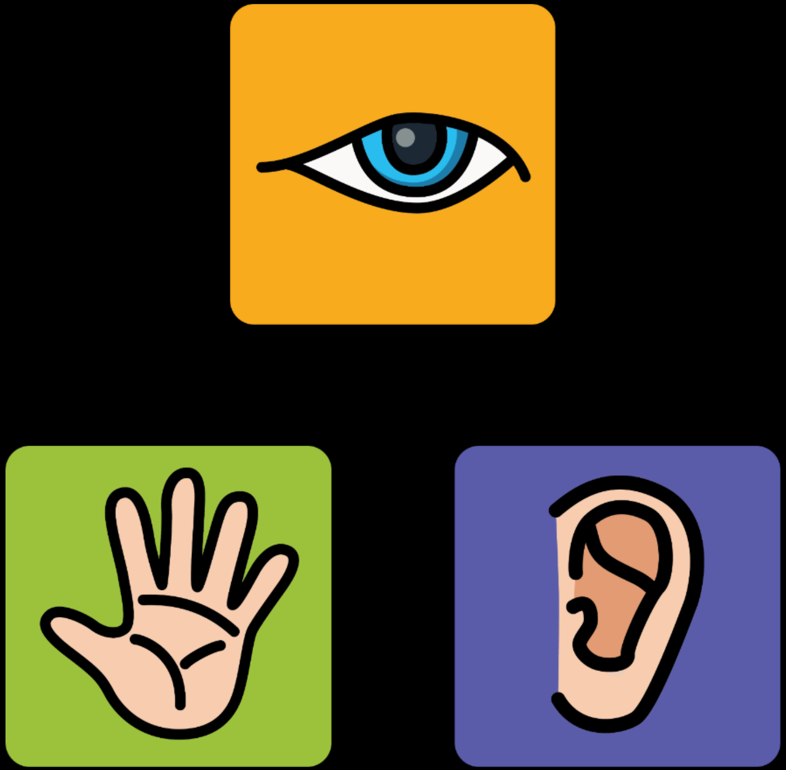
A Photophoretic-trap volumetric display

D. E. Smalley, et al., Nature 553, 486-490 (2018)

- Create 3D images using Persistence of Vision (PoV)
- Particle needs to be scanned in PoV time (≤ 0.1 s)

Multimodal Acoustic Trapping Display (MATD)

R. Hirayama, D. Martinez-Plasencia, N. Masuda, S. Subramanian, Nature 575, 320-323 (2019)



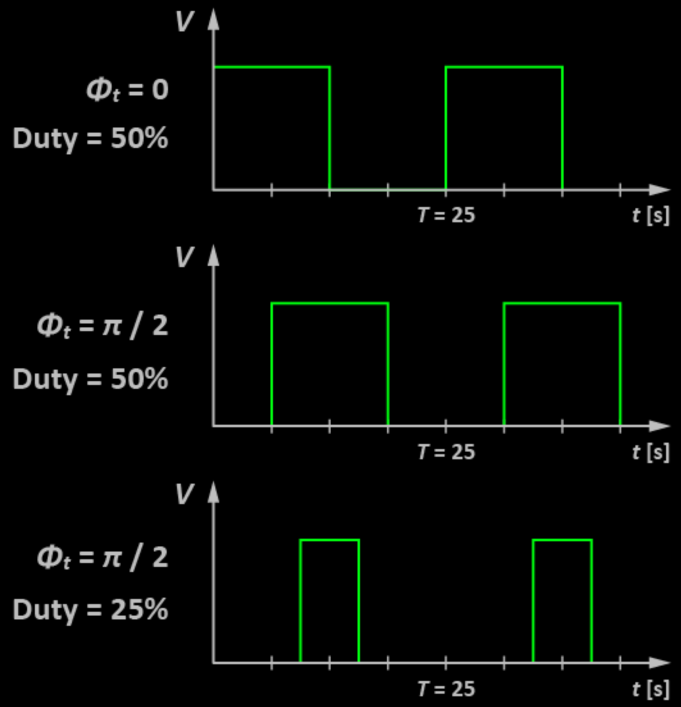
The MATD creates:

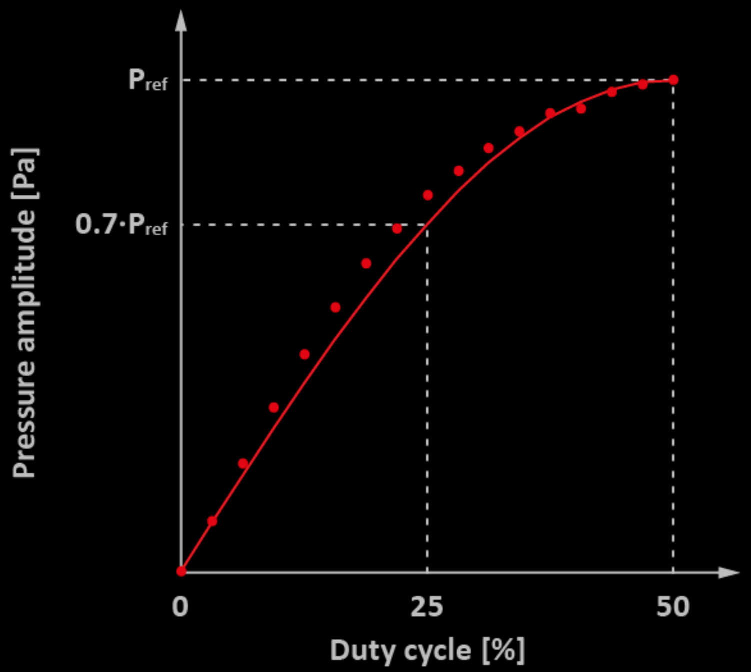
- Visual content by making use of PoV
- Tactile content by focusing acoustic pressure
- Audio content by using amplitude modulation

Operating Principles of the MATD

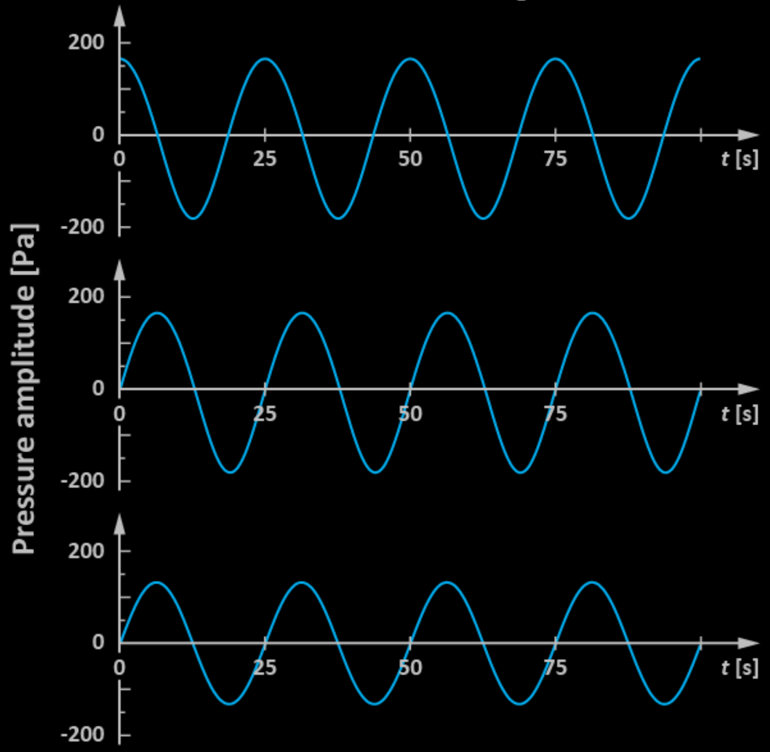
Control of transducers

Transducer control → Amplitude mapping → Transducer response

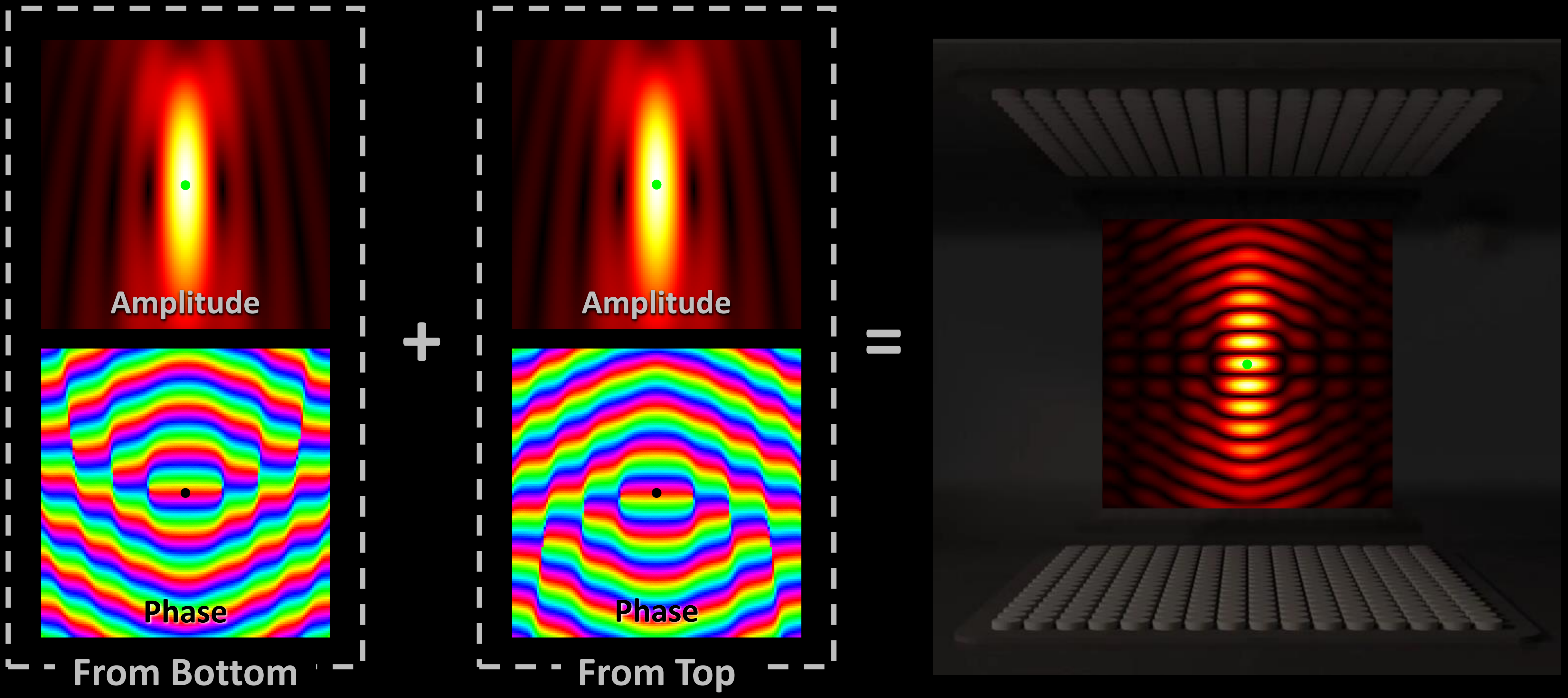




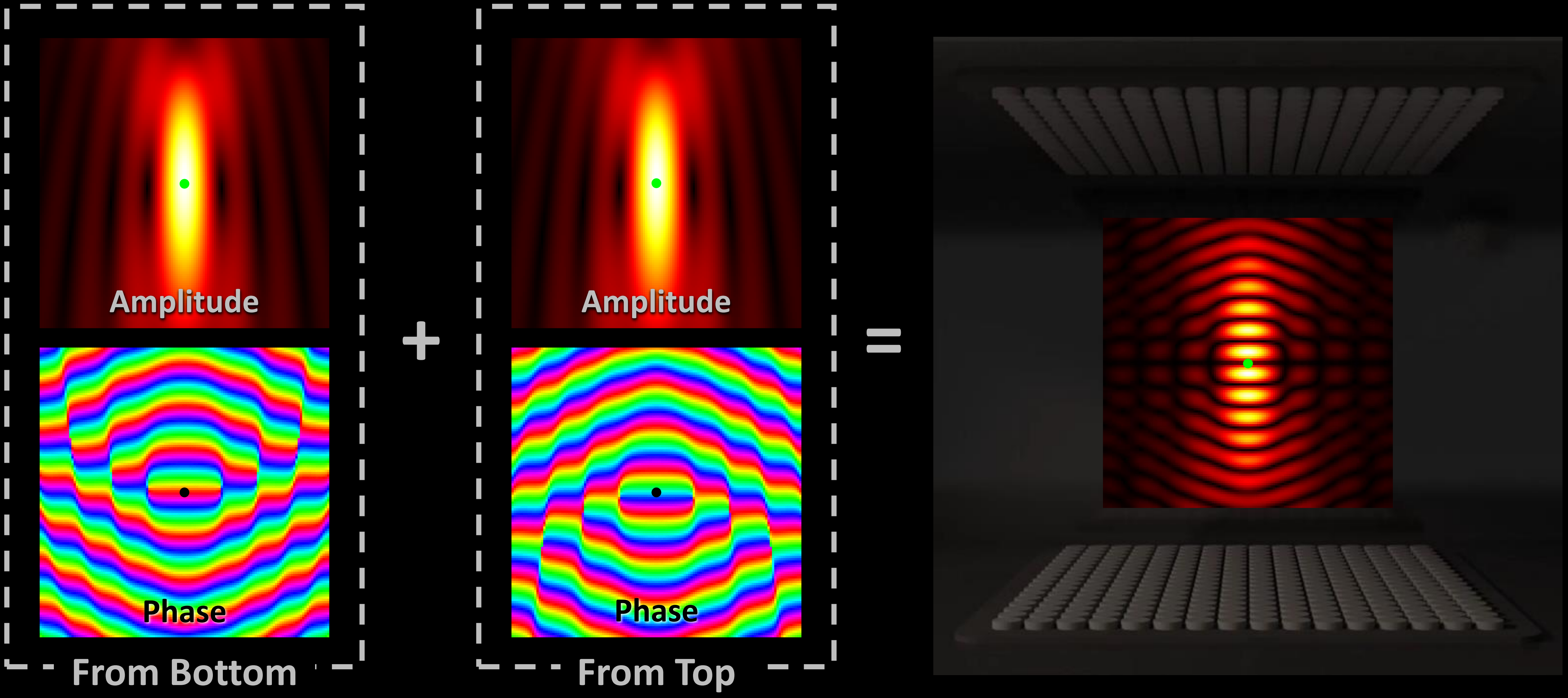
$$A = P_{ref}\sqrt{\sin^2\left(\frac{duty}{100}\pi\right)}$$



Creation of focusing points (tactile)

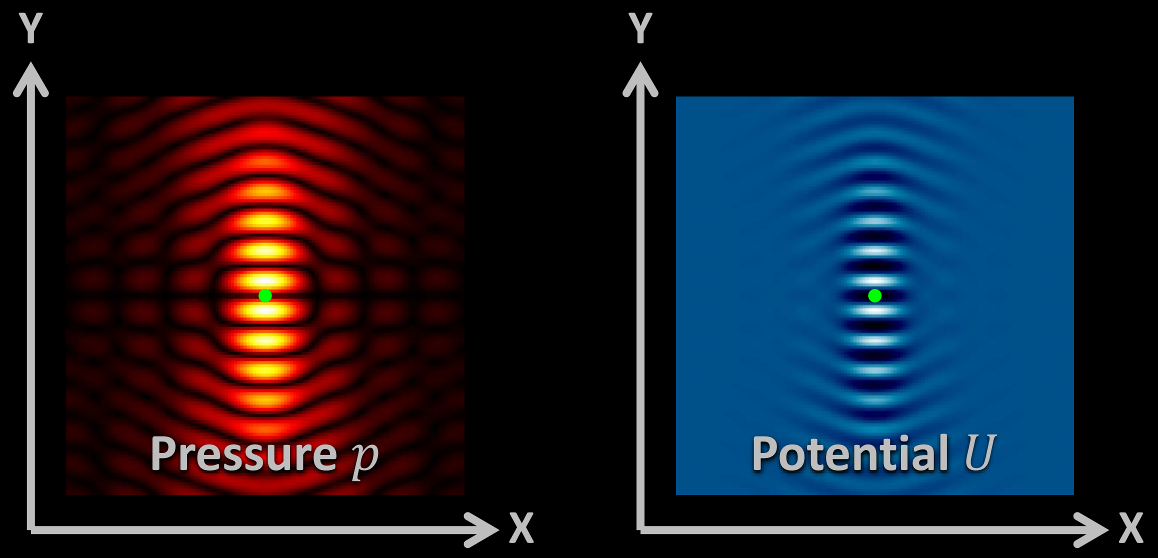


Creation of levitation traps (visual)

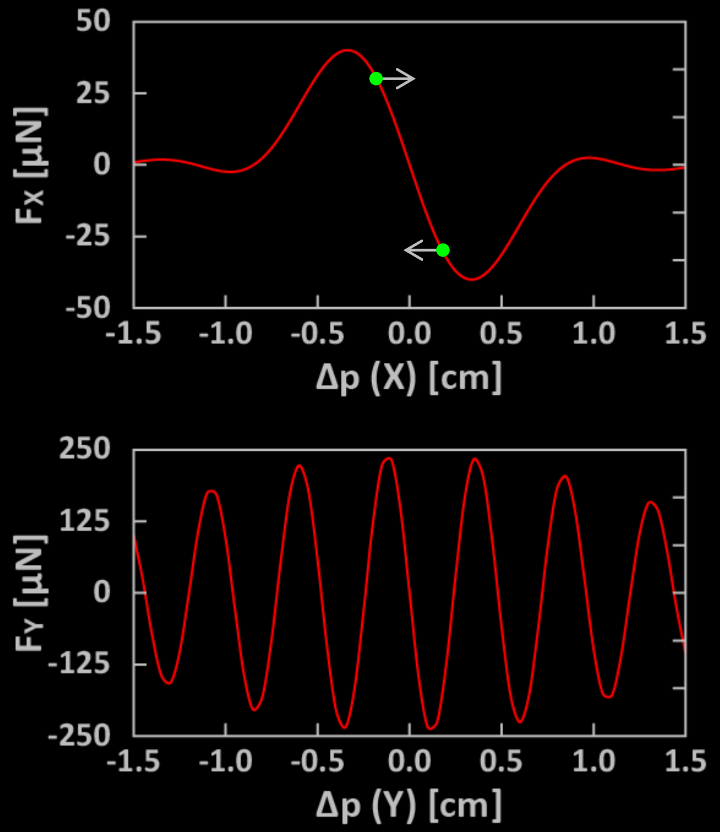


Acoustic radiation force

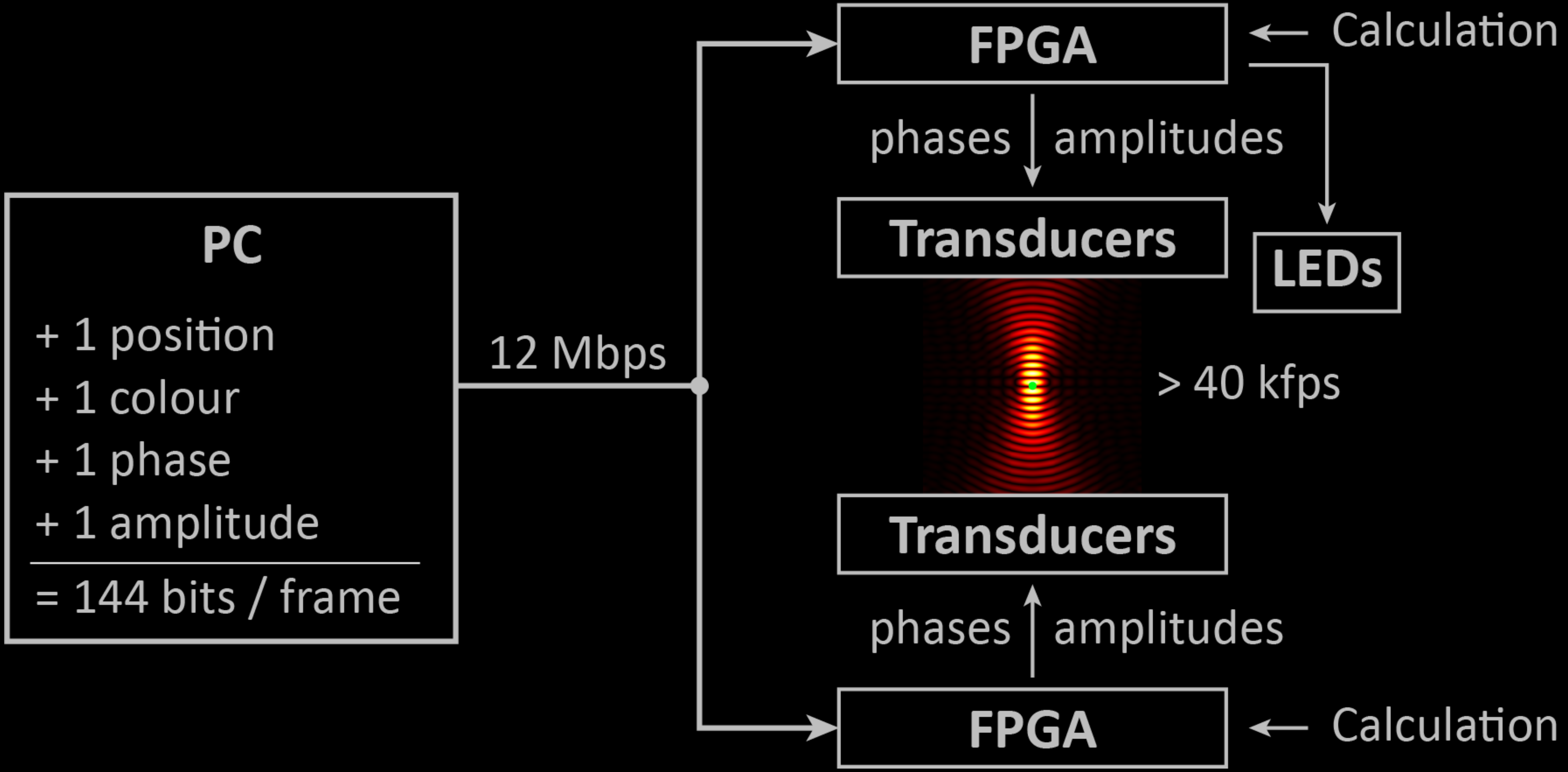
- Gor'kov potential U can be determined by incoming acoustic pressure and its derivative
- Force can be approximated as: $\boldsymbol{F} = -\nabla U$ when particle is much smaller than wavelength



$$U = K_1(|p|^2) - K_2\left(\left|\frac{\partial p}{\partial x}\right|^2 + \left|\frac{\partial p}{\partial y}\right|^2 + \left|\frac{\partial p}{\partial z}\right|^2\right)$$



Control system

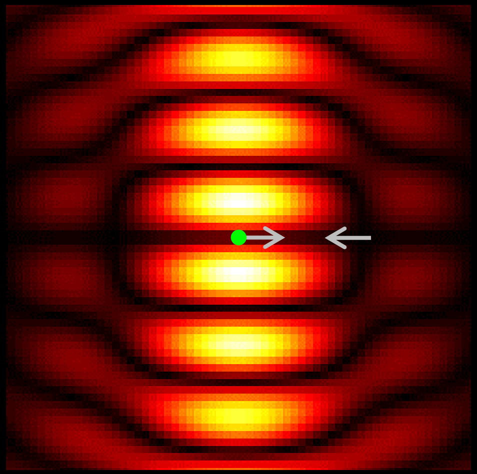


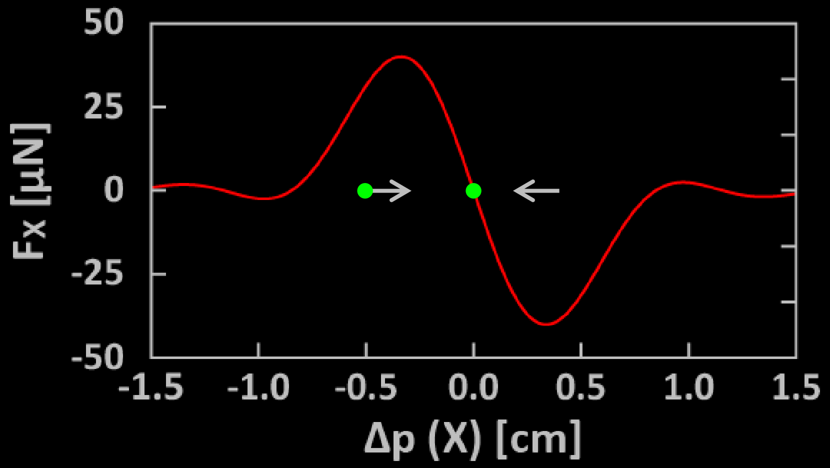
Performance of the MATD

Position updates

Other levitators:

- When the trap is moved, the particles have enough time to transition to a static equilibrium
- It can result in uneven accelerations of the particle and is not suitable for PoV applications

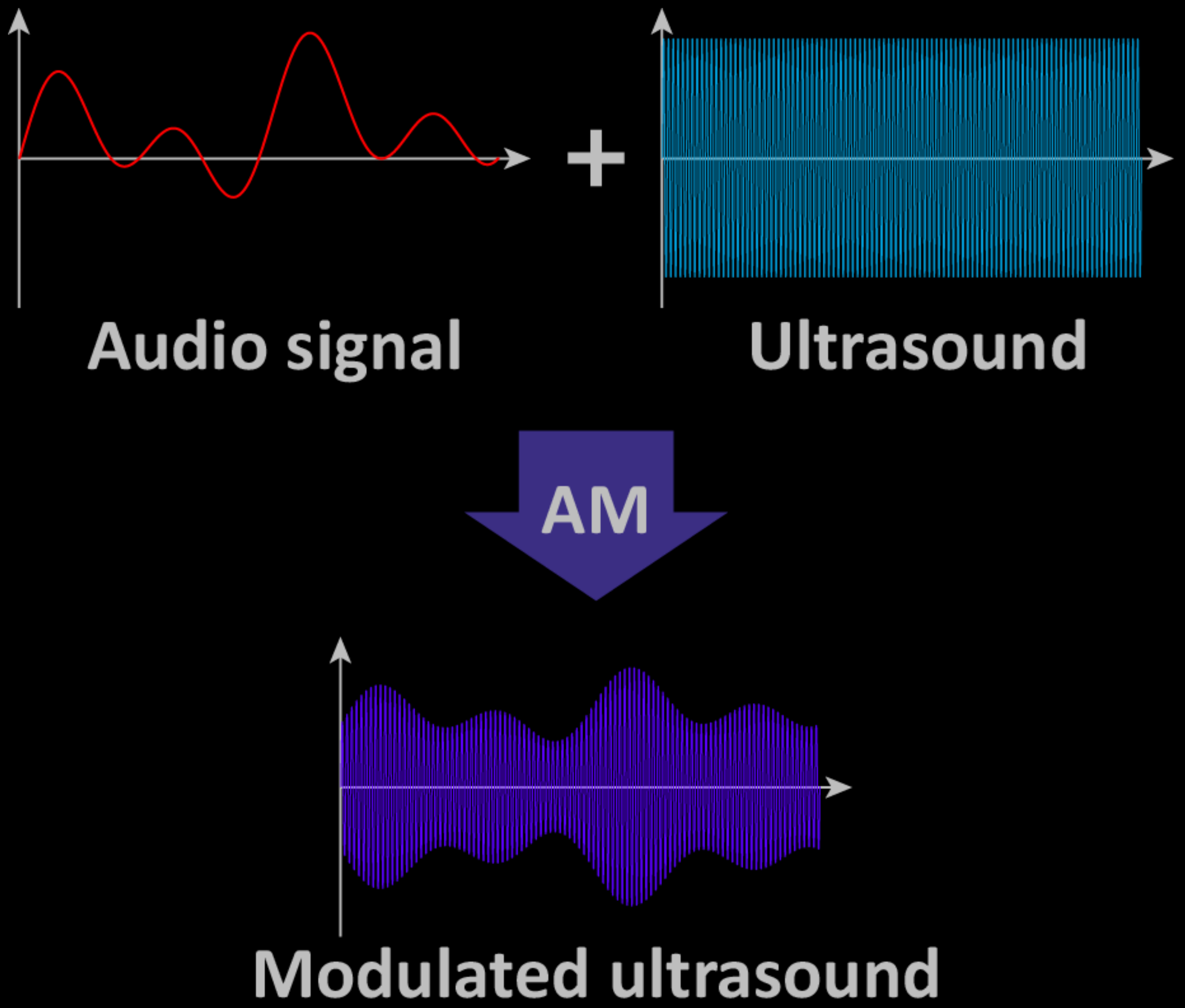




MATD:

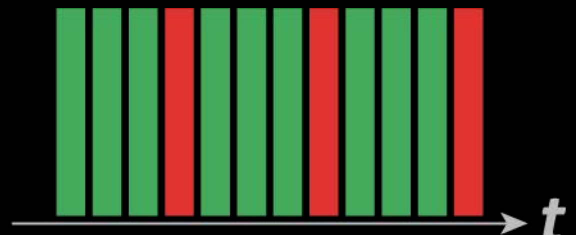
- The particles do not reach such a static equilibrium after each update of 40 kHz
- This enables high accelerations and speeds, allowing creation of PoV content

Audio creation using amplitude modulation

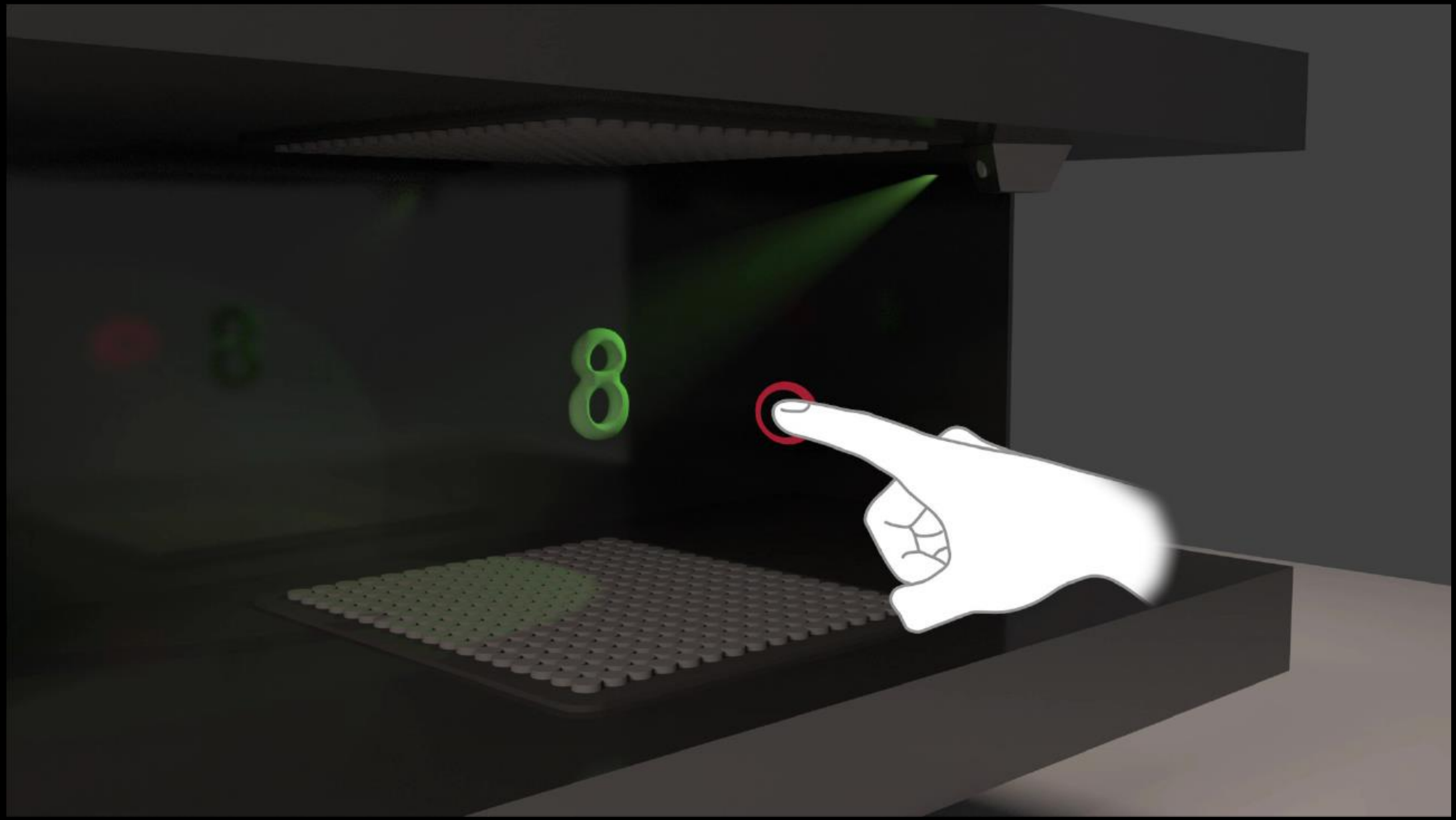


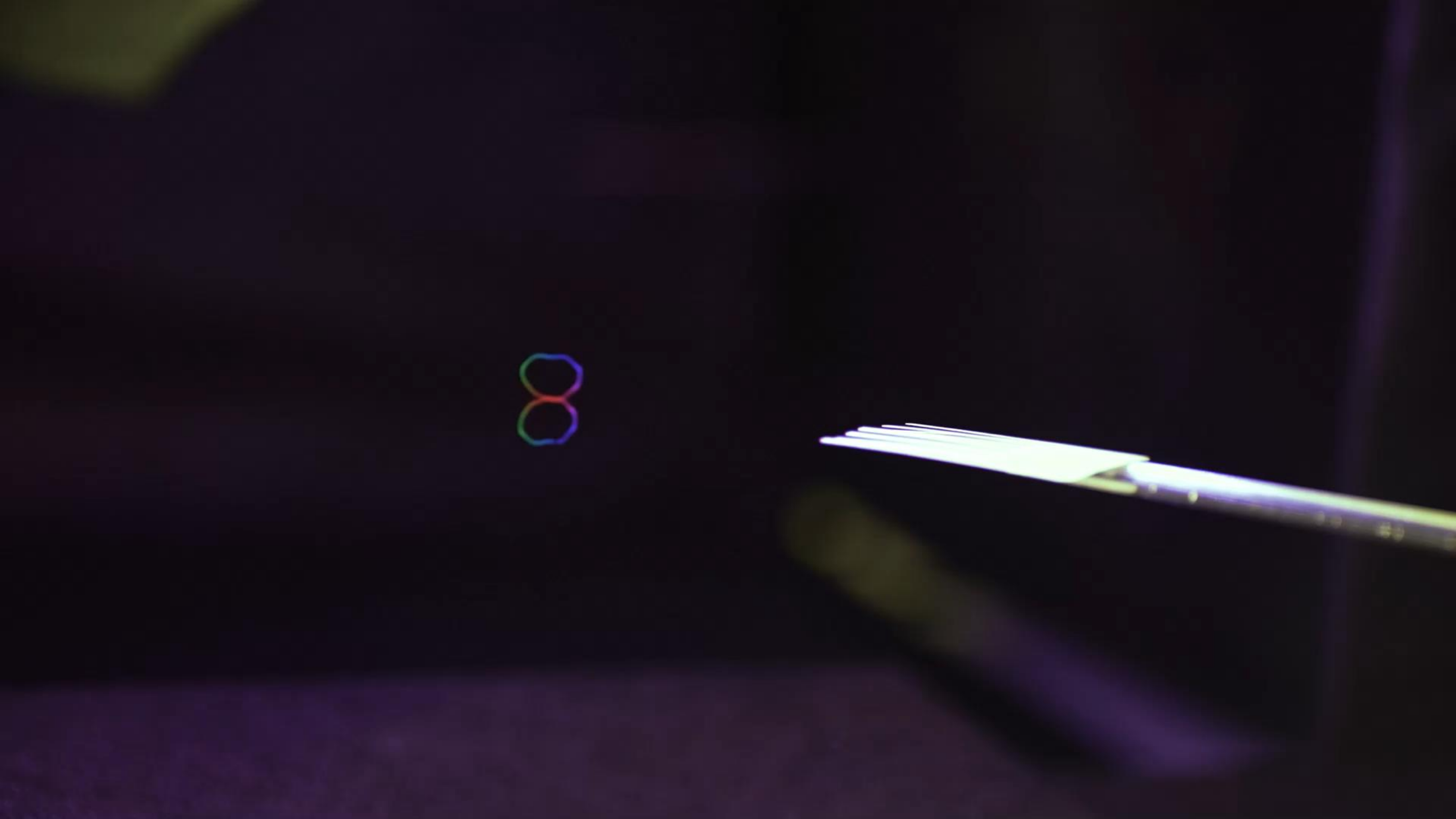
$$A_m(t) = \ (1 + m\, g_a(t)) \cdot \cos(\omega_c t)$$

Tactile delivery using time-multiplexing



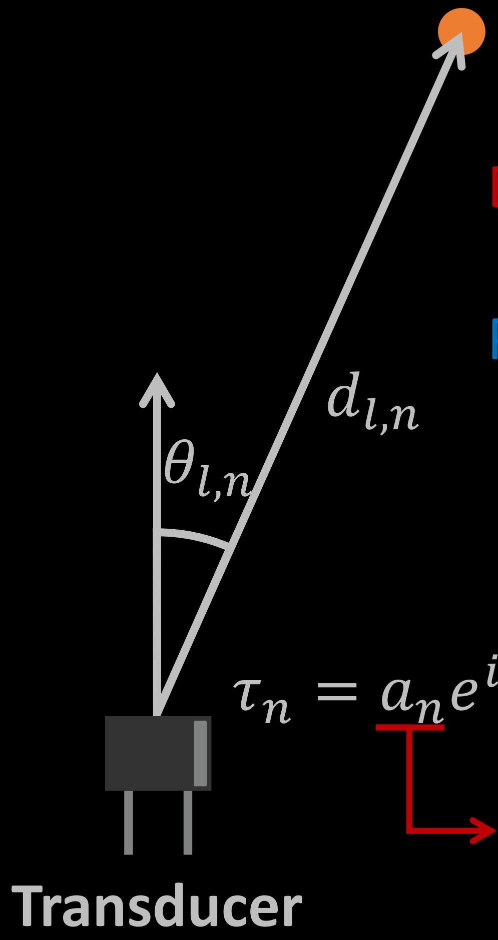
Position multiplexing





Multipoint Algorithm

Model of PATs

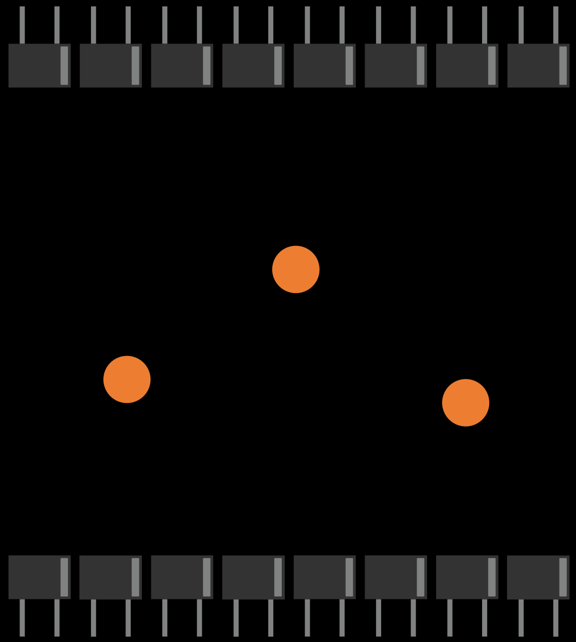


$$\zeta_l = P_{n,l}\Phi_{n,l}\tau_n$$

Directivity: $P_{n,l} = \dfrac{P_{ref}}{d_{l,n}} \dfrac{2J_1(kr\sin\theta_{l,n})}{kr\sin\theta_{l,n})}$

Phase delay: $\Phi_{n,l} = e^{(kd_{l,n})i}$

$$\tau_n = \underbrace{a_n}_{\text{Amplitude}} e^{i\underbrace{\varphi_n}_{\text{Phase}}}$$



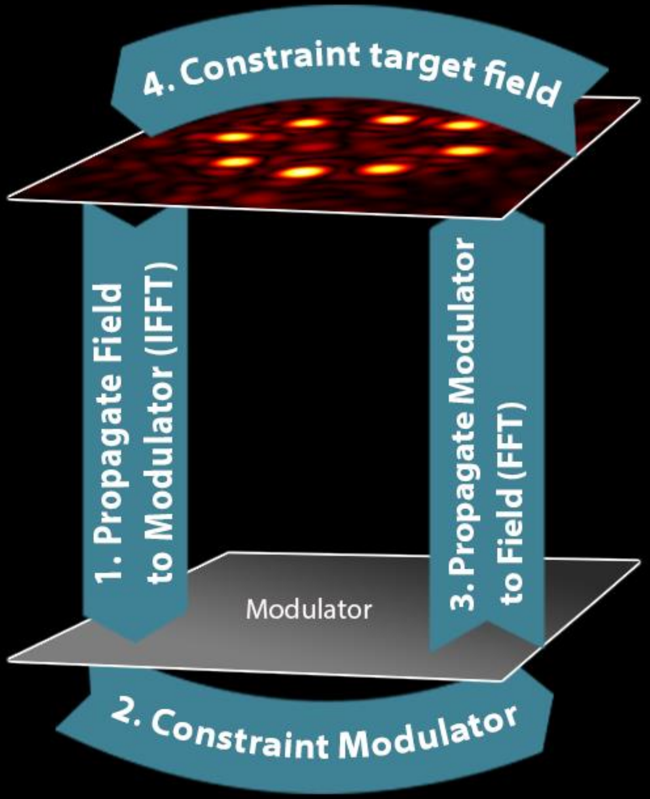
Pressure of transducers: $\boldsymbol{\tau} = [\tau_1, \tau_2 \cdots \tau_N]^T$

Pressure of points: $\boldsymbol{\zeta} = [\zeta_1, \zeta_2 \cdots \zeta_L]^T$

$$\boldsymbol{\zeta} = \underbrace{\boldsymbol{F}}_{\text{Transmission Matrix}}\boldsymbol{\tau} = \begin{bmatrix} P_{1,1}\Phi_{1,1} & \cdots & P_{1,N}\Phi_{1,N} \\ \vdots & \ddots & \vdots \\ P_{L,1}\Phi_{L,1} & \cdots & P_{L,N}\Phi_{L,N} \end{bmatrix}\boldsymbol{\tau}$$

GS-based phase retrieval method

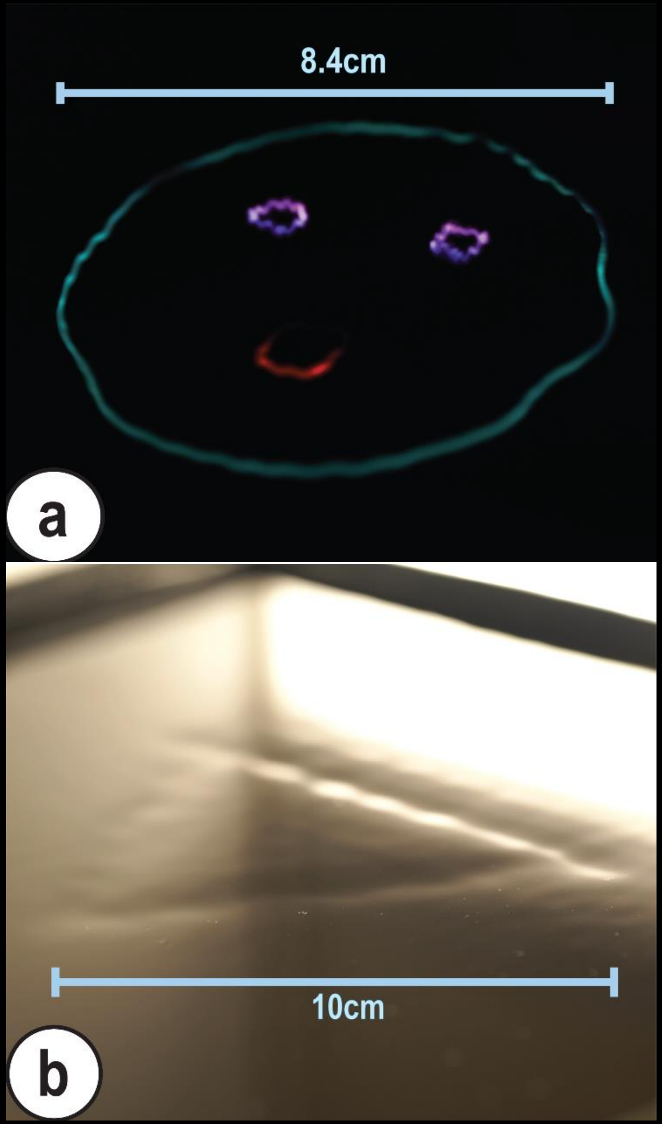
- Phase of each point can be optimized by repeating backward- and forward propagations
- The approach is not fast enough to create multimodal content



1. $\boldsymbol{\tau}^{(k)} = \boldsymbol{F}^{H}\boldsymbol{\zeta}^{(k)}$
2. $\boldsymbol{\tau}^{(k)} = \left\{\dfrac{\tau_n^{(k)}}{\left|\tau_n^{(k)}\right|}, n = 1 \dots N\right\}$
3. $\boldsymbol{\zeta}^{(k)} = \boldsymbol{F}\boldsymbol{\tau}^{(k)}$
4. $\boldsymbol{\zeta}^{(k+1)} = \left\{\dfrac{\zeta_l^{(k)}}{\left|\zeta_l^{(k)}\right|}, l = 1 \dots L\right\}$

GS-PAT: high-speed multipoint sound control

D. Martinez-Plasencia, R. Hirayama, R. Montano, S. Subramanian, SIGGRAPH 2020 Technical papers (2020)

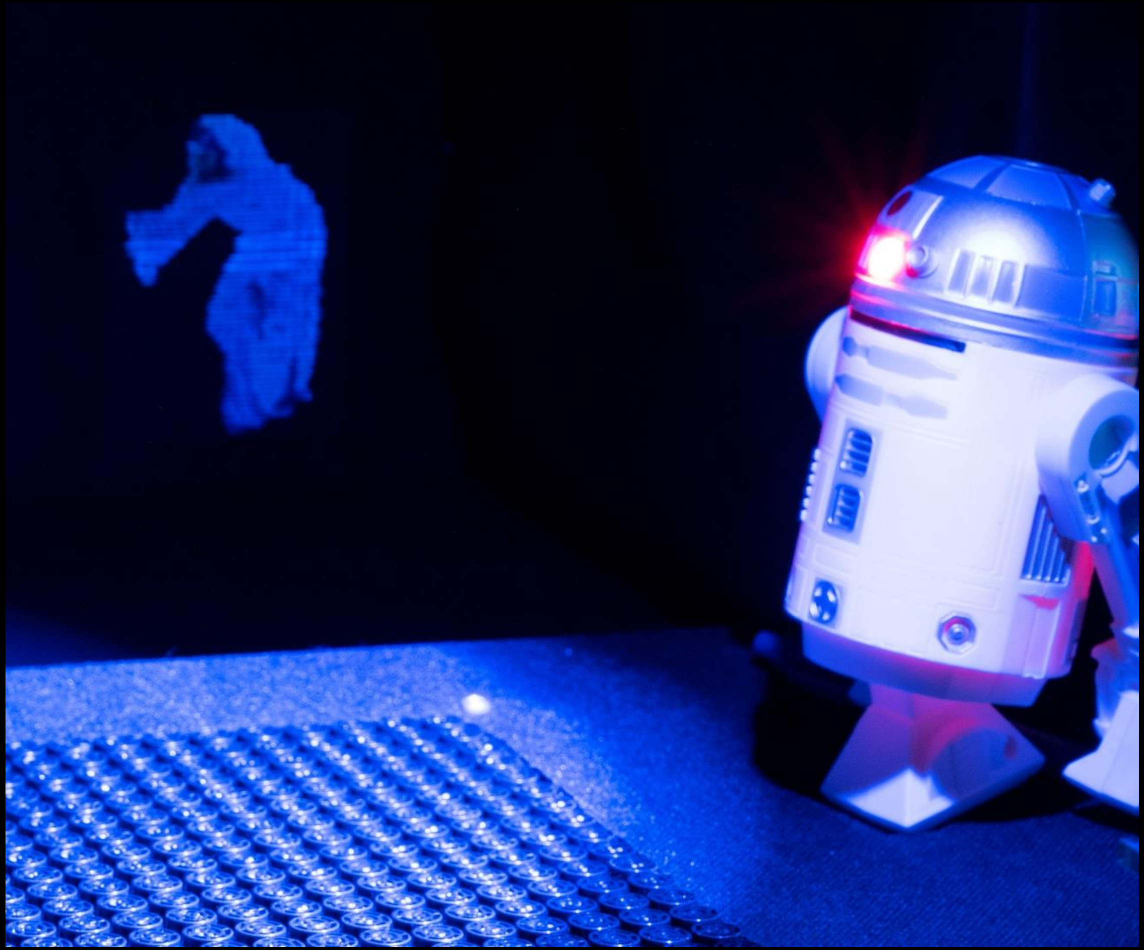


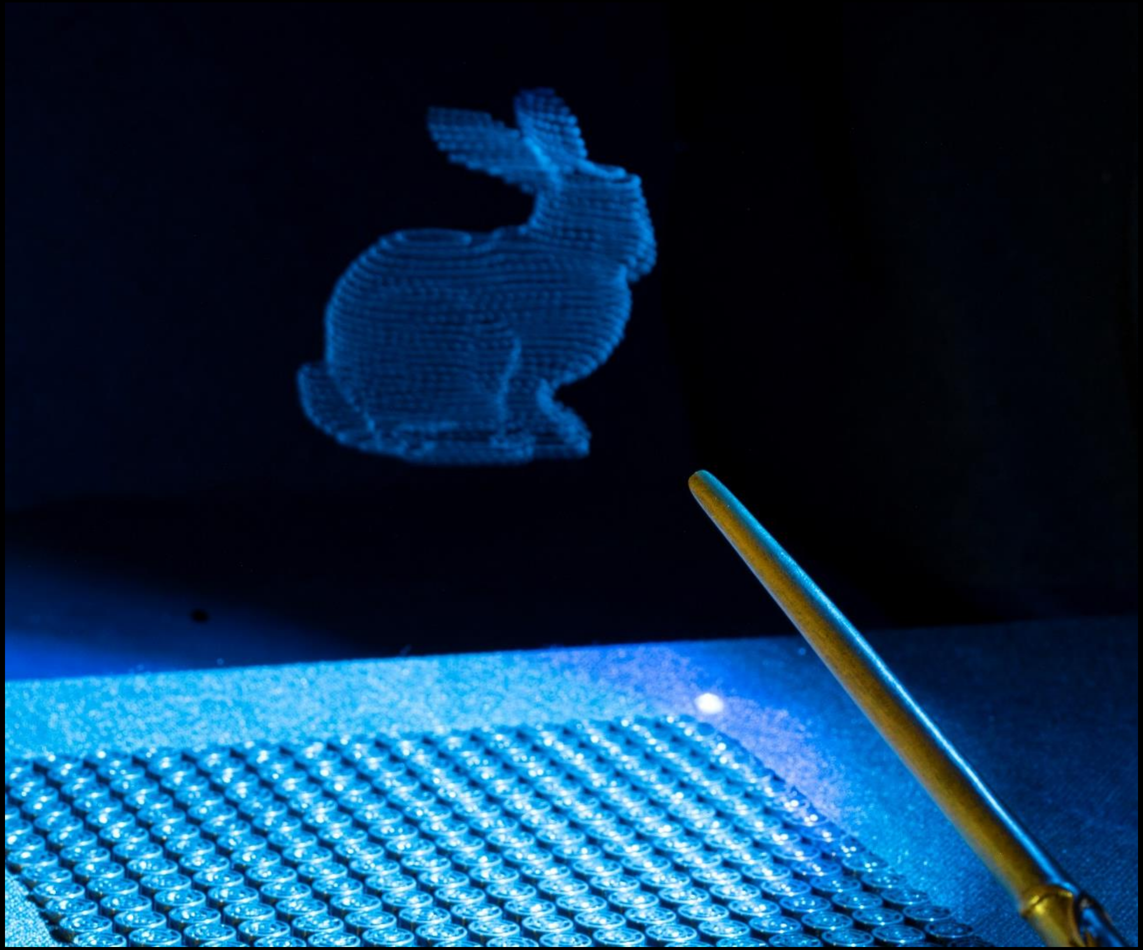
GS-PAT:

- Approximates GS algorithms
- Computes multiple geometries in parallel (GPU)
- Achieves over 17,000 updates per second

Computing sound fields at such high rates enables a range of novel applications...

Thanks for listening





*Shutter speeds: 20 seconds

UNIVERSITY OF CAMBRIDGE

360-degree 3D light field display

Dr Ali Özgür Yöntem

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Department of Computer Science and Technology

OPTICA - Display Technology Technical Group Chair

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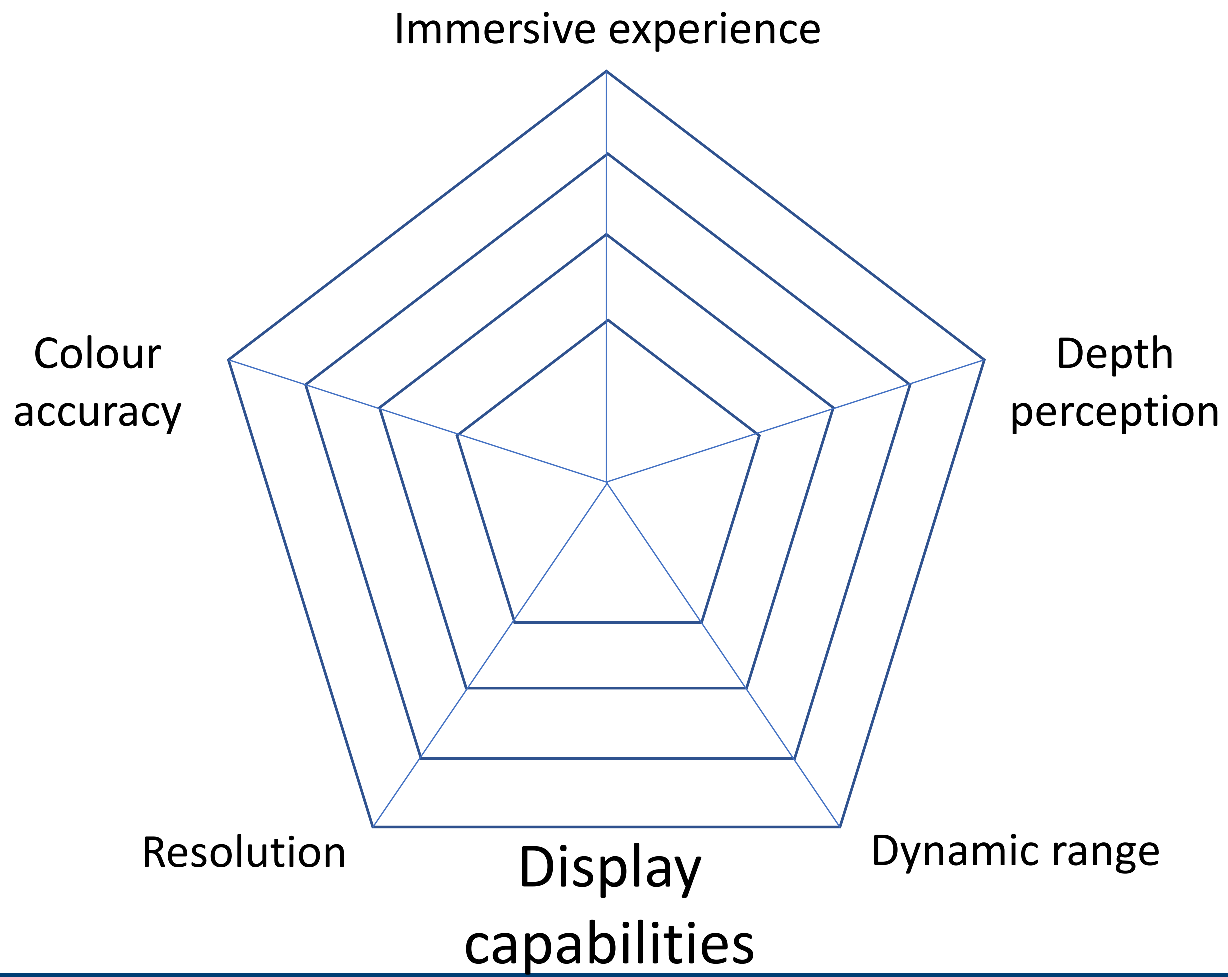
Highlights

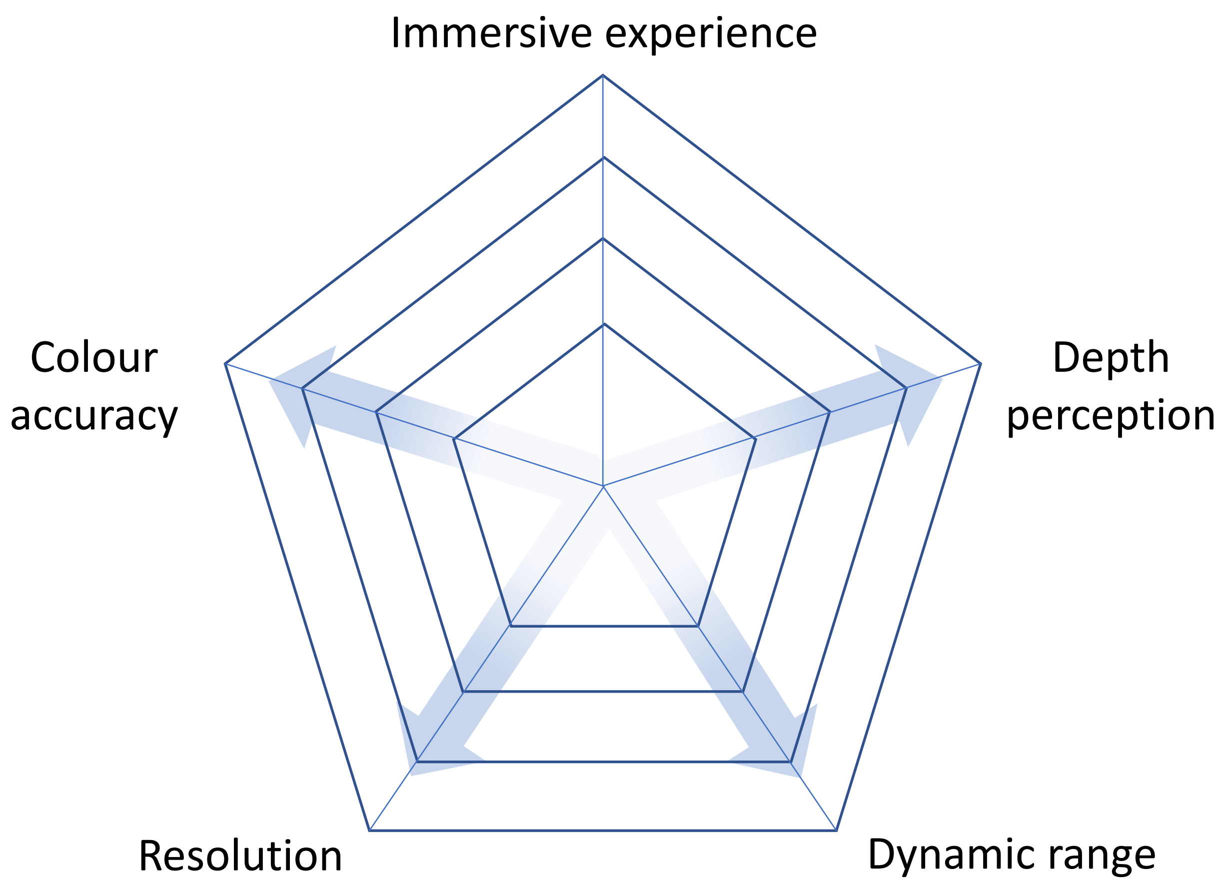
- Realistic, immersive, and 3D displays
- Reproducing reality
- 360-degree displays

Realistic, immersive, and 3D displays

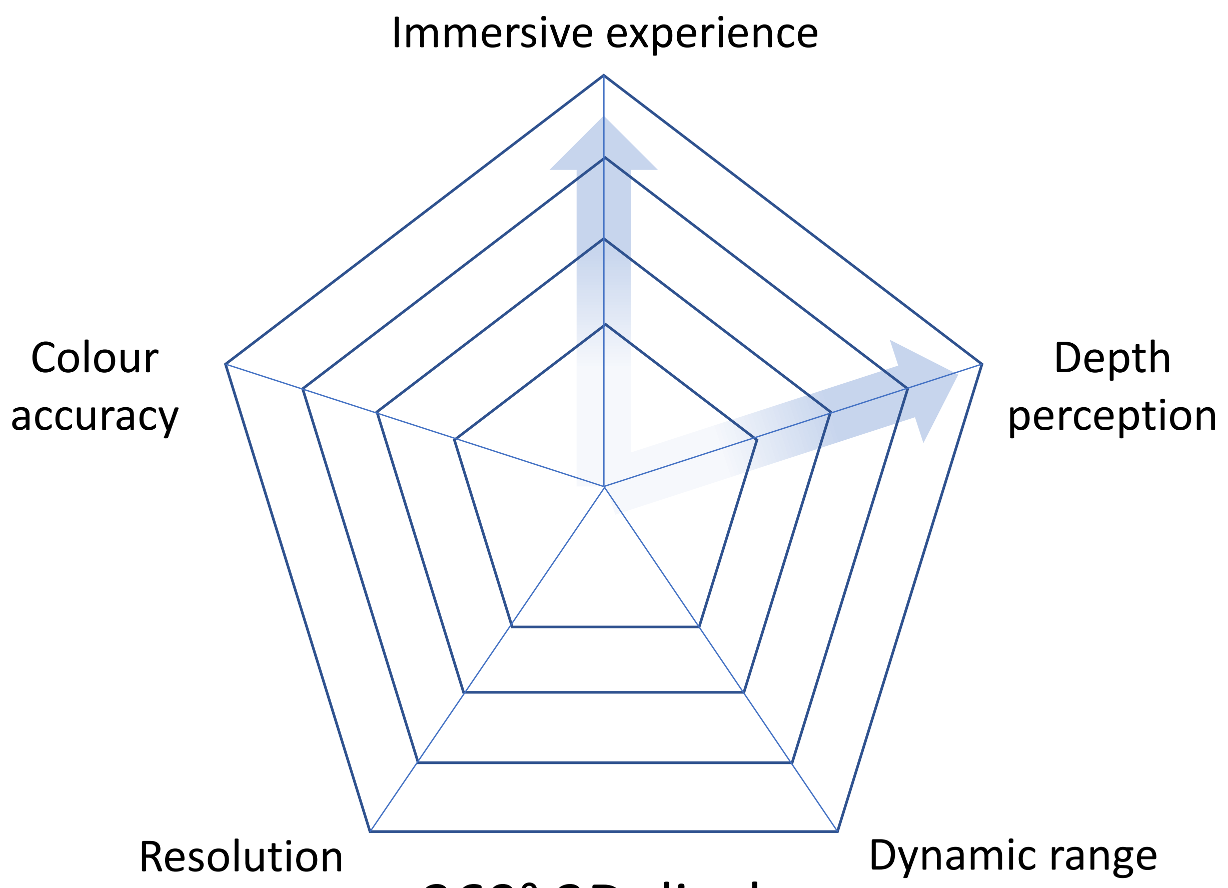
- Resolution
- Dynamic range
- Colour accuracy
- Depth perception, e.g., depth of field, accommodation-vergence, etc.
- Immersive experience, e.g., field of view and viewing angle



Realistic, immersive, and 3D displays

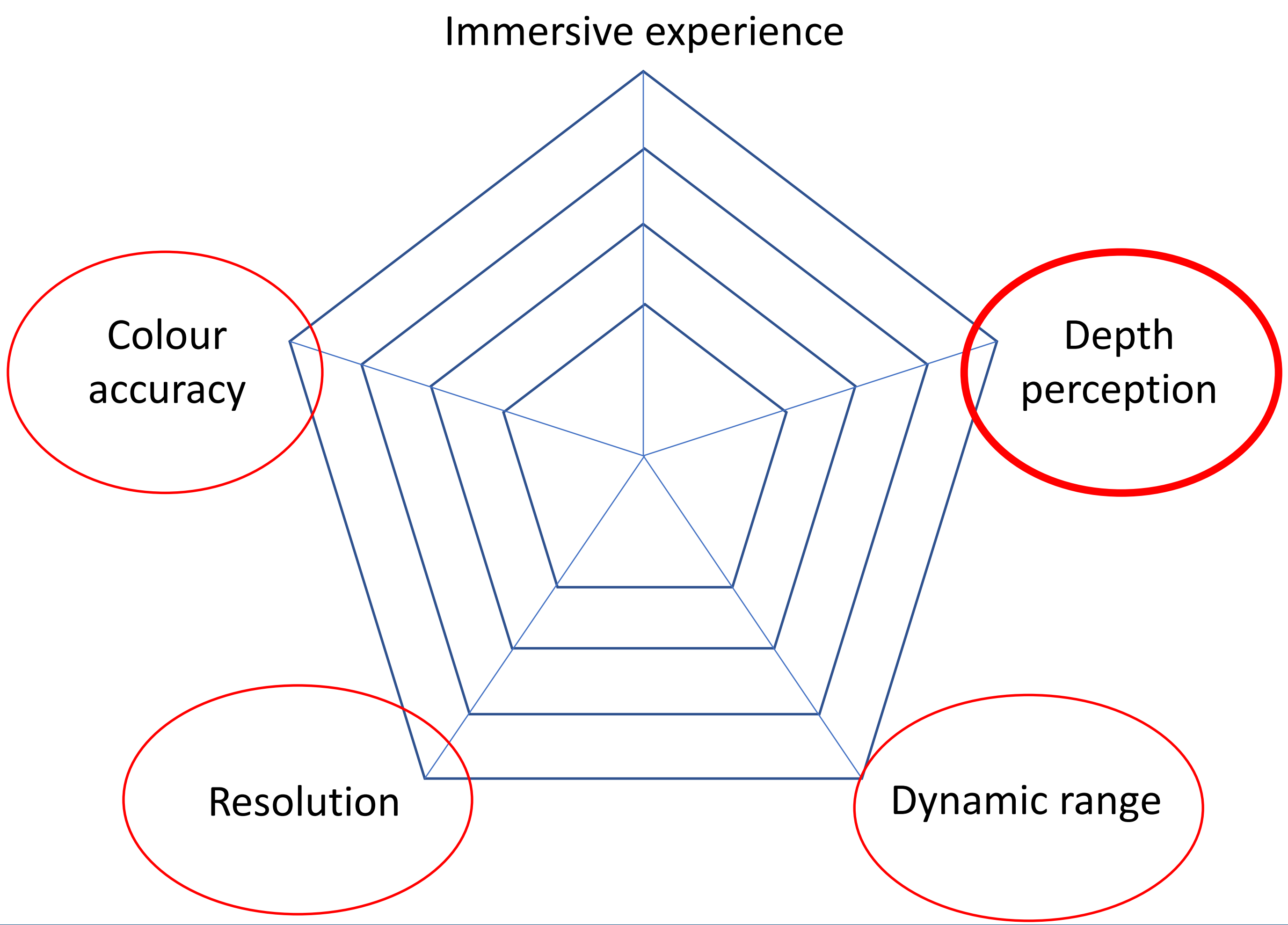


HDR + 3D

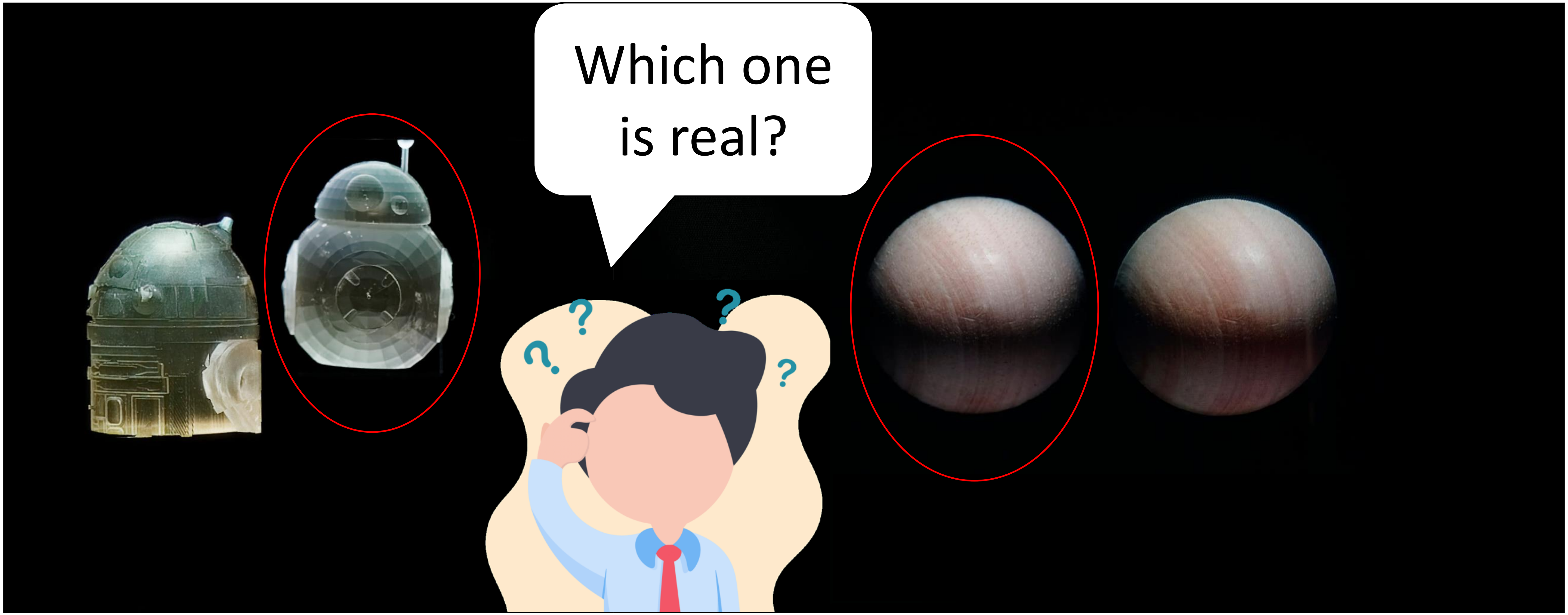


360° 3D display

Visual Turing Test



Reproducing reality - Visual Turing Test



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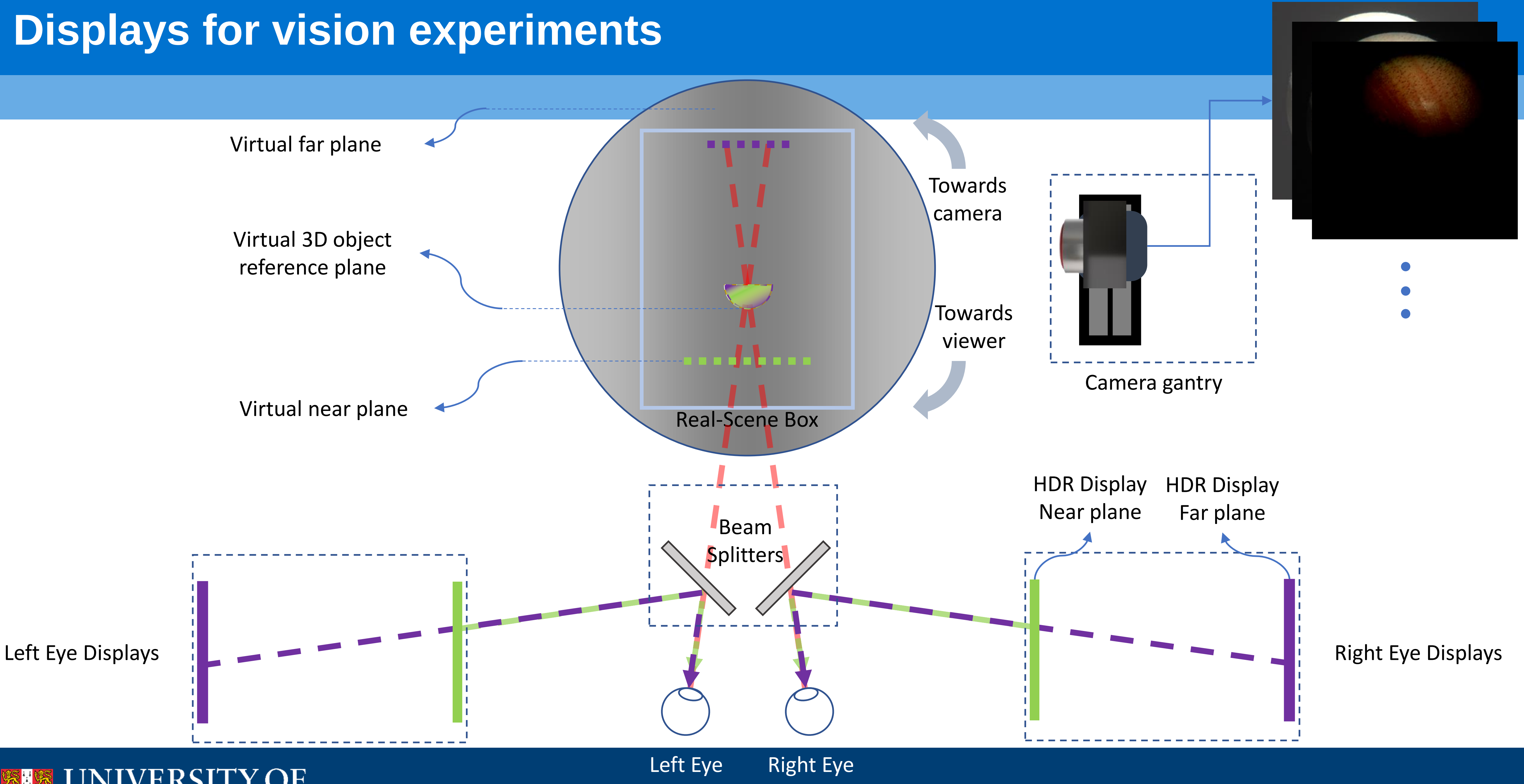
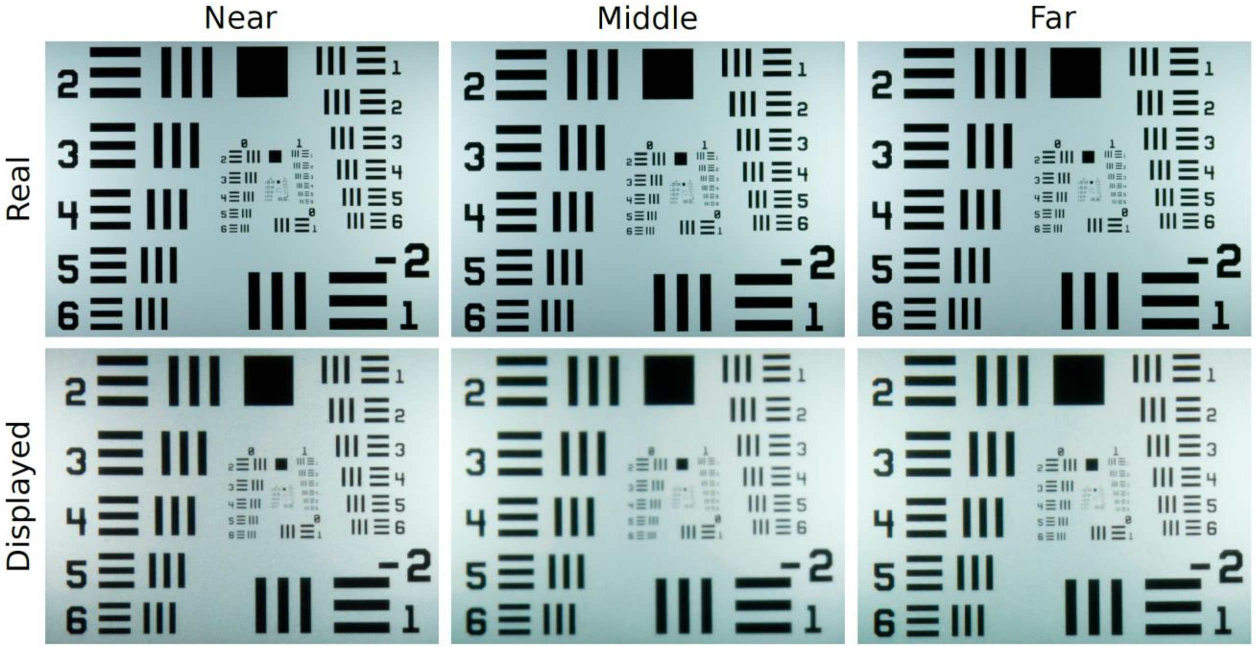
F. Zhong, A. Jindal, **A. Ö. Yöntem**, P. Hanji, S. Watt, and R. Mantiuk, "Reproducing Reality with High Dynamic Range Multifocal Stereo Display" **SIGGRAPH Asia**, (2021).
https://www.cl.cam.ac.uk/research/rainbow/projects/hdrmfs/

Displays for vision experiments



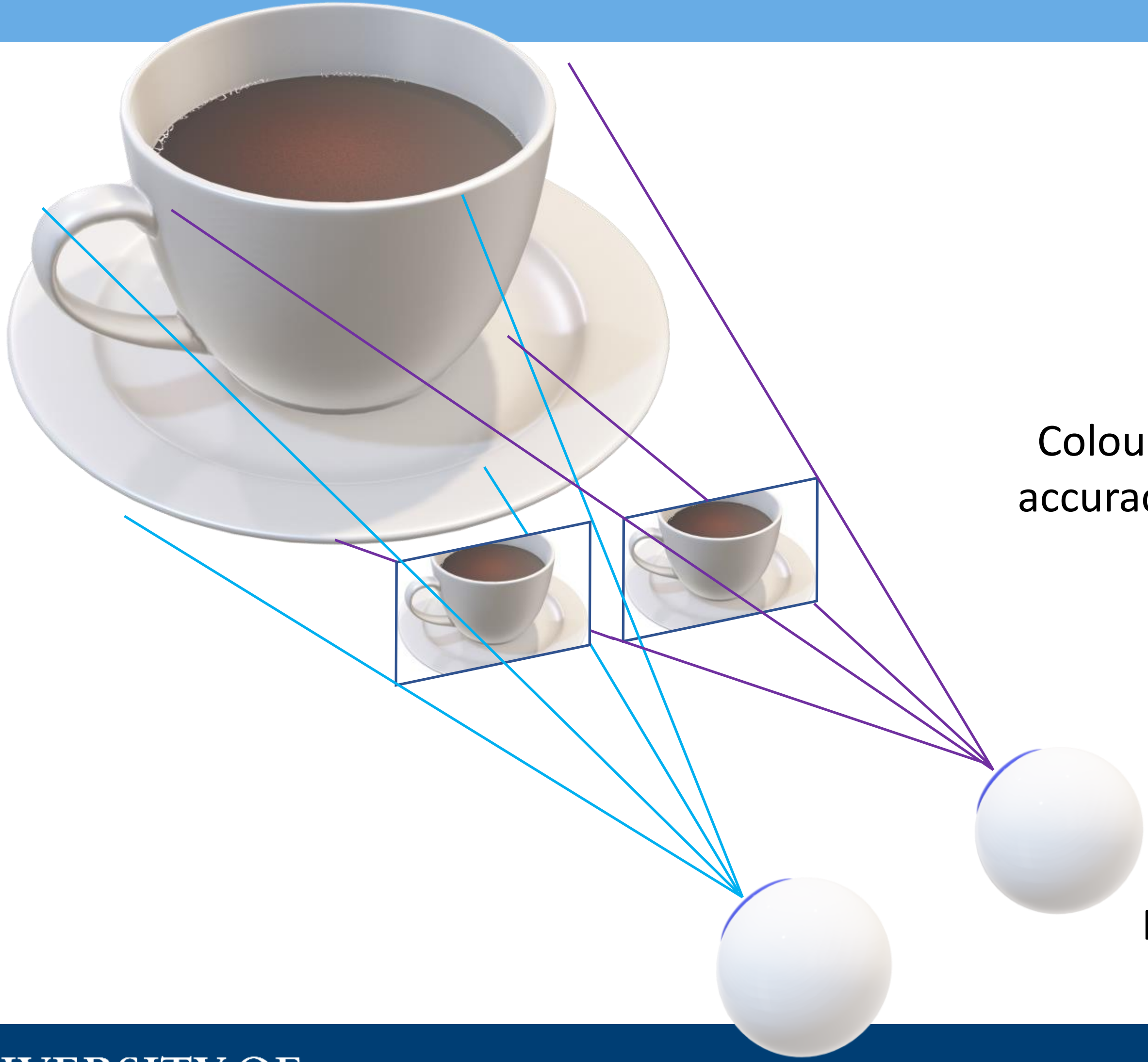
Reproducing reality

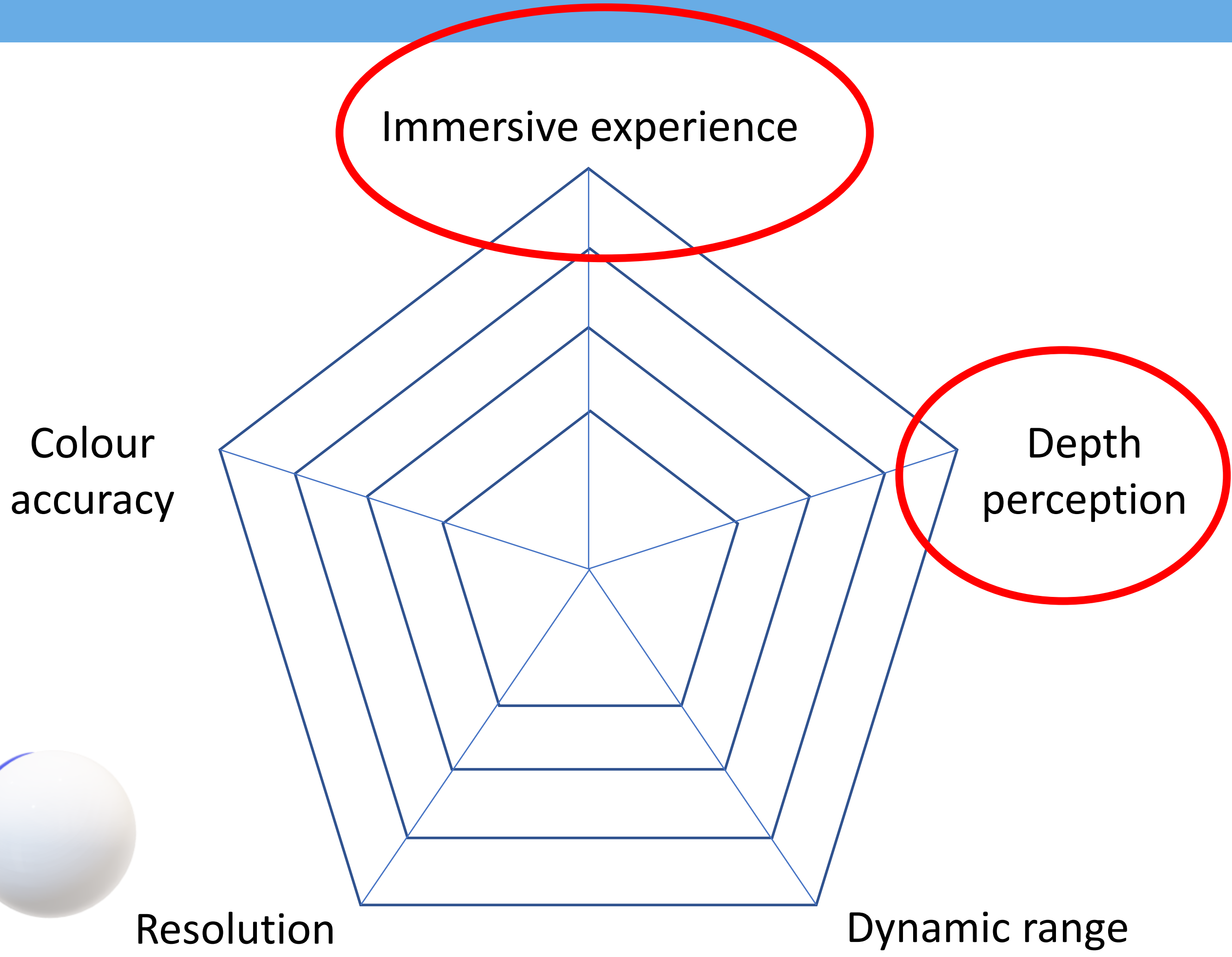


- High resolution,
- High dynamic range,
- High colour accuracy,
- Defocus blur by multi-focal stack,
- Stereoscopic 3D.

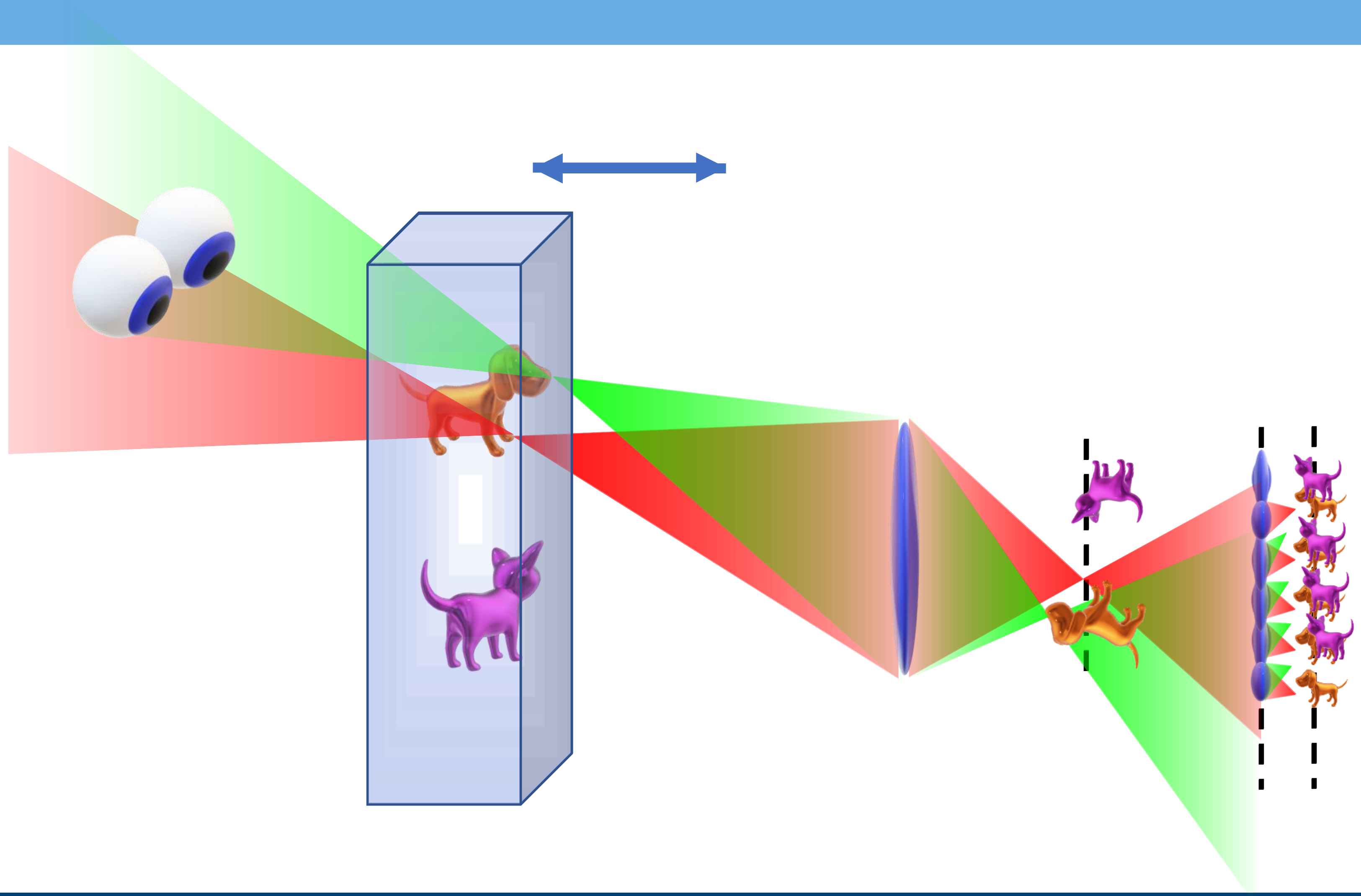
F. Zhong, A. Jindal, **A. Ö. Yöntem**, P. Hanji, S. Watt, and R. Mantiuk, "Reproducing Reality with High Dynamic Range Multifocal Stereo Display" **SIGGRAPH Asia**, (2021).

Light field displays





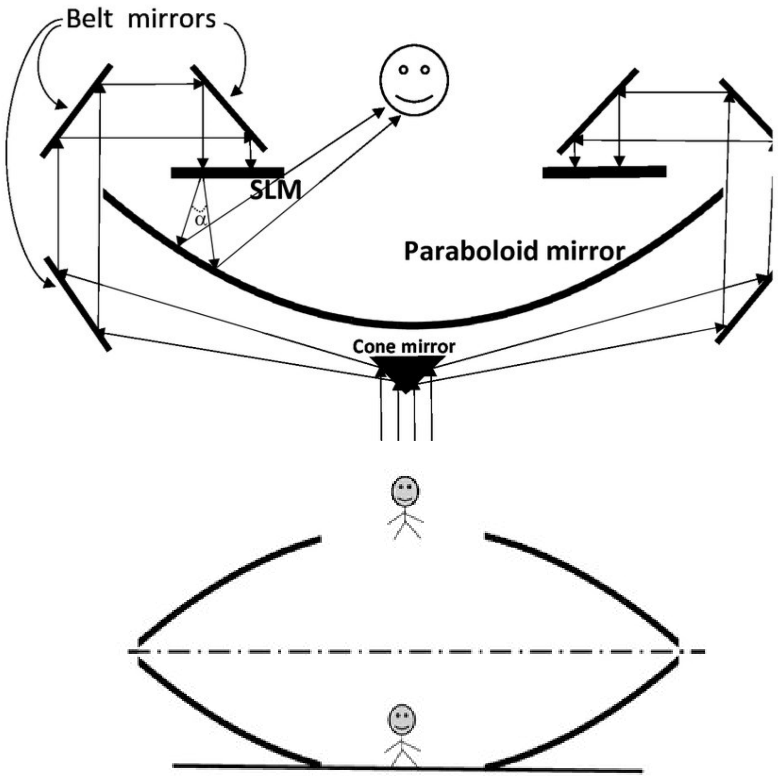
Light field displays



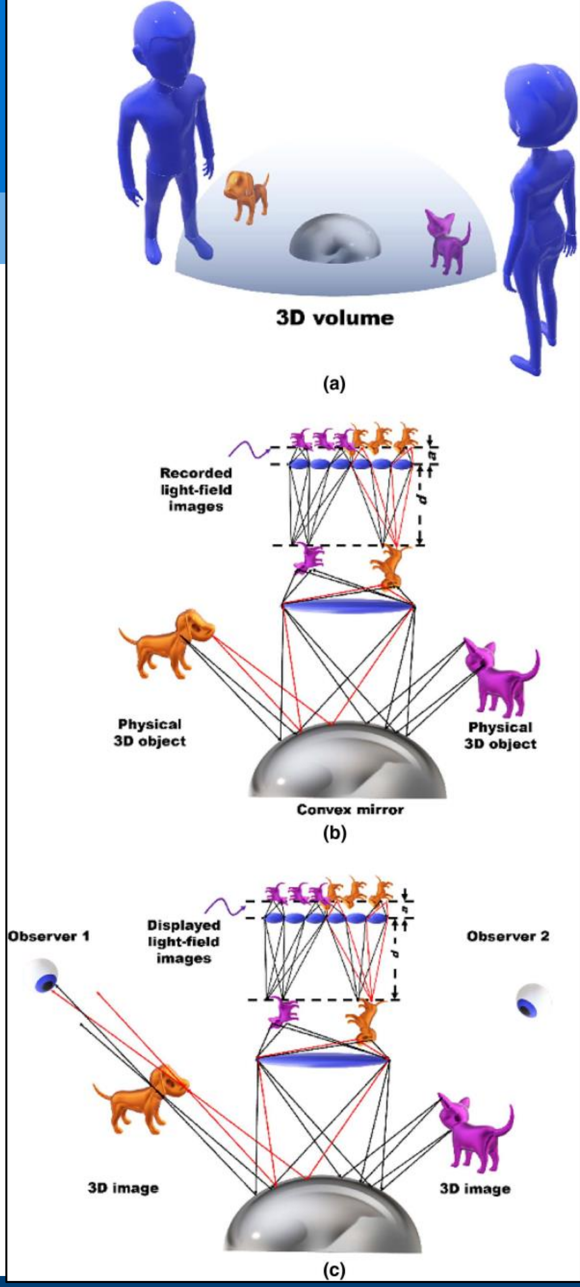
360 degree displays

360 degree displays

L. Onural, “Design of a 360-degree holographic 3D video display using commonly available display panels and a paraboloid mirror”, Proc. SPIE, vol. 10126, 2017.

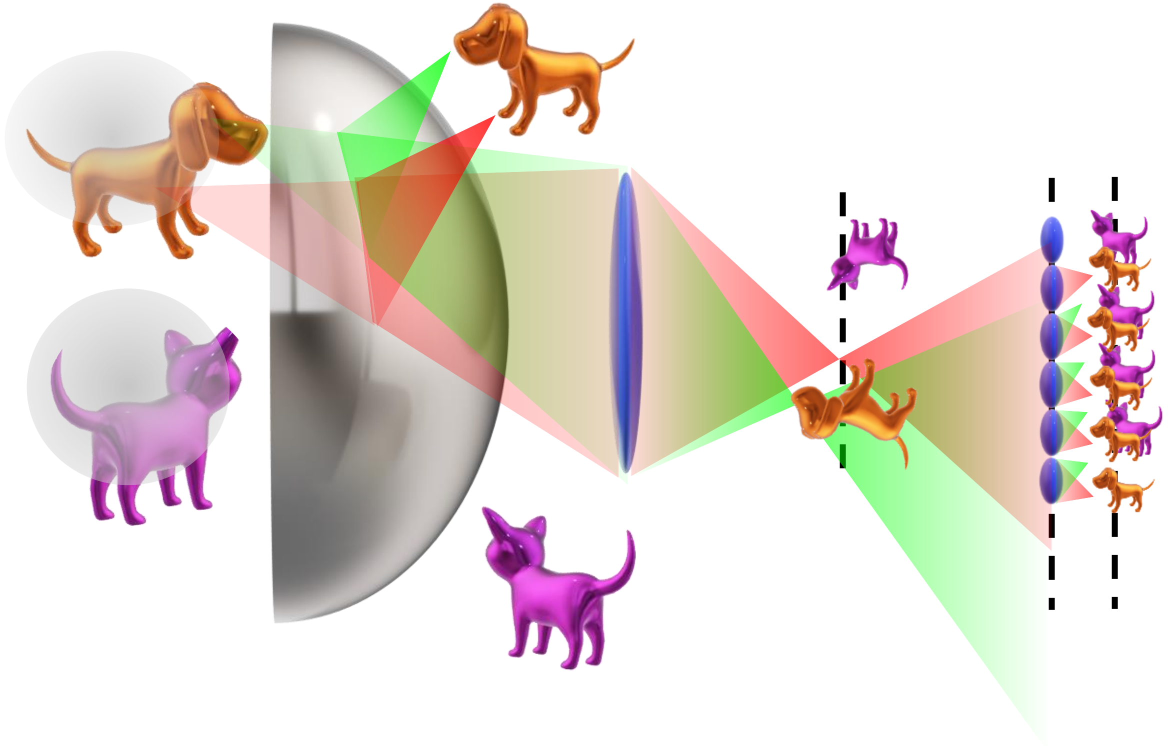


Shunsuke Yoshida, "fVisiOn: 360-degree viewable glasses-free tabletop 3D display composed of conical screen and modular projector arrays," Opt. Express 24, 13194-13203 (2016).



A. Ö. Yöntem, et al. “Reciprocal 360-deg 3D light-field image acquisition and display system **[invited]**,” **J. Opt. Soc. Am. A**, vol. **36,** no. 2, pp. A77-A87, 2019.
Spotlight on Optics article by OSA.

360-degree 3D light field display



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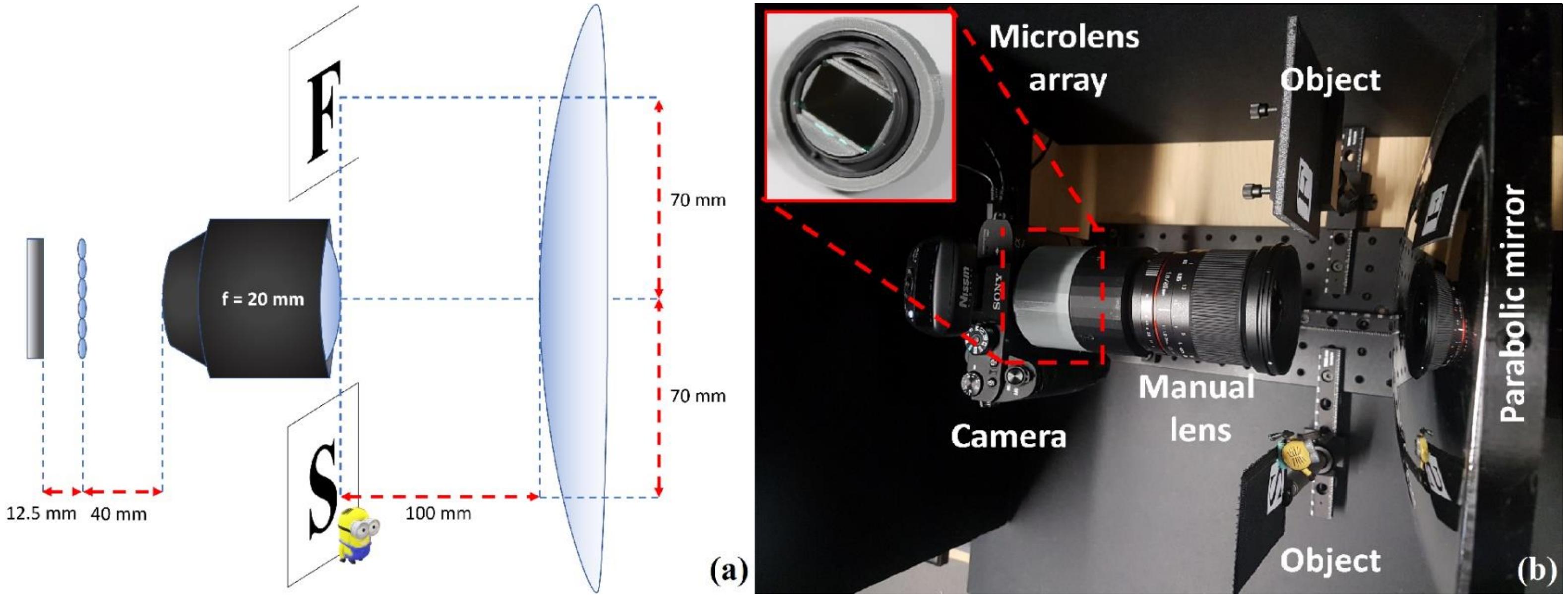

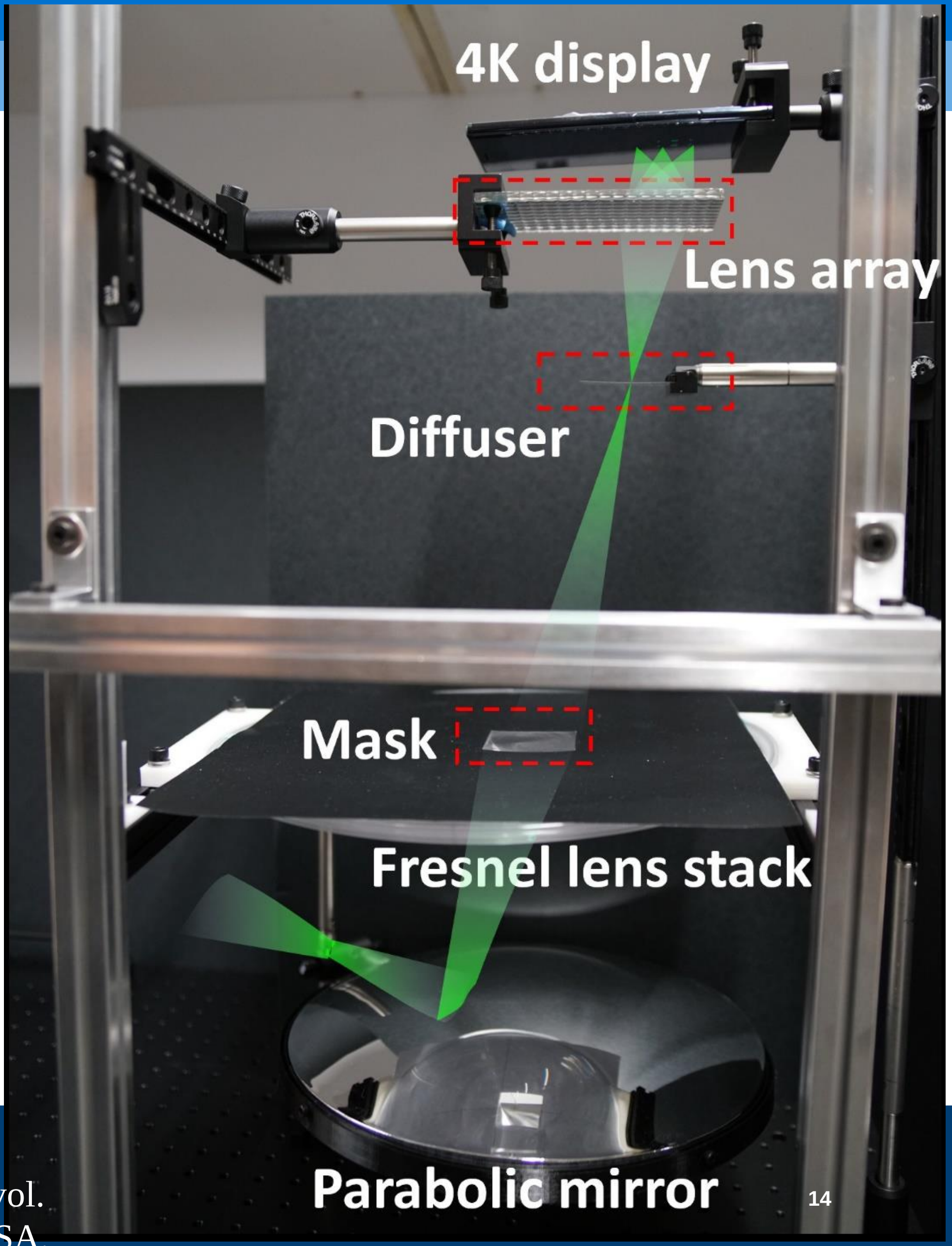

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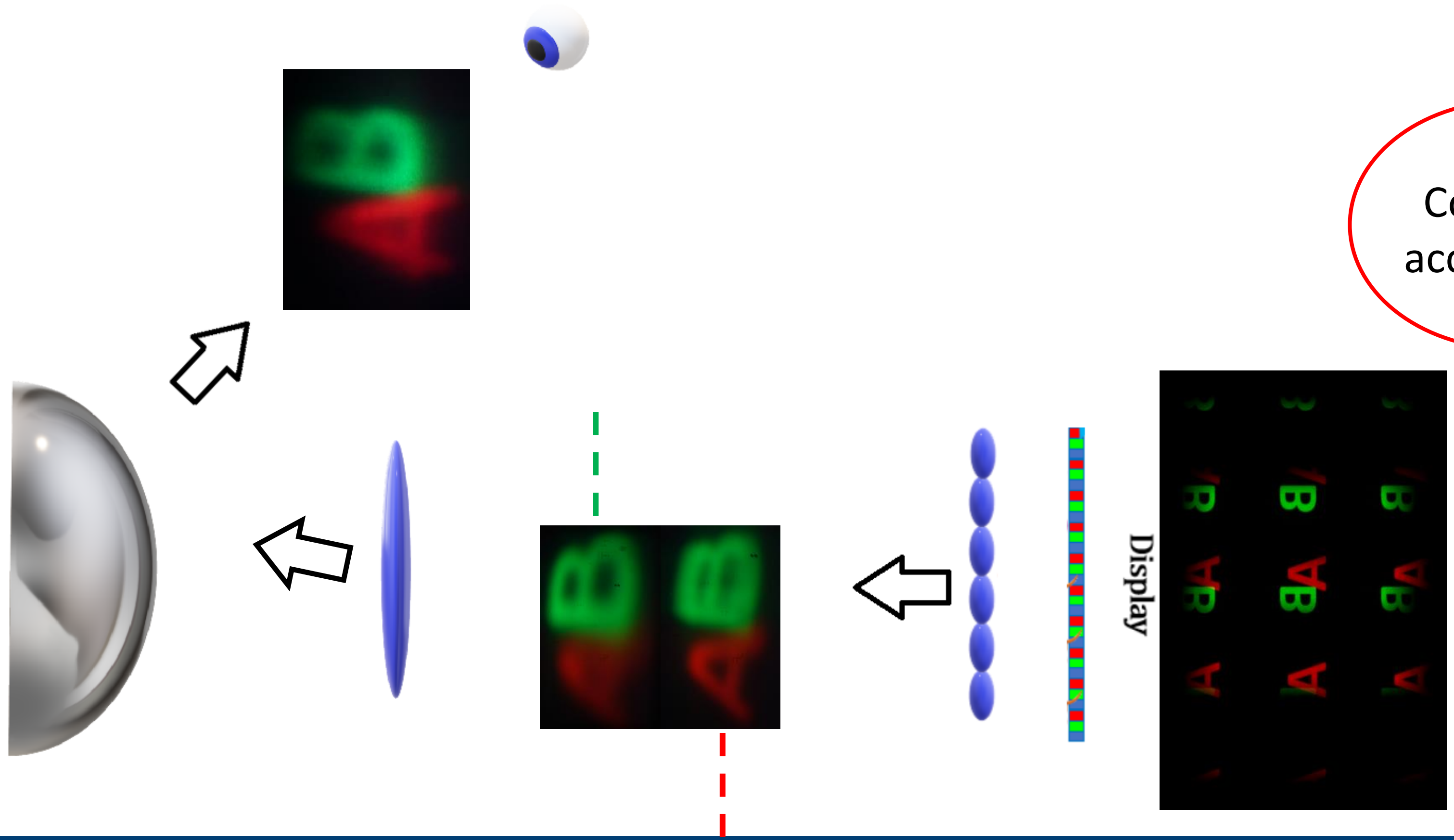
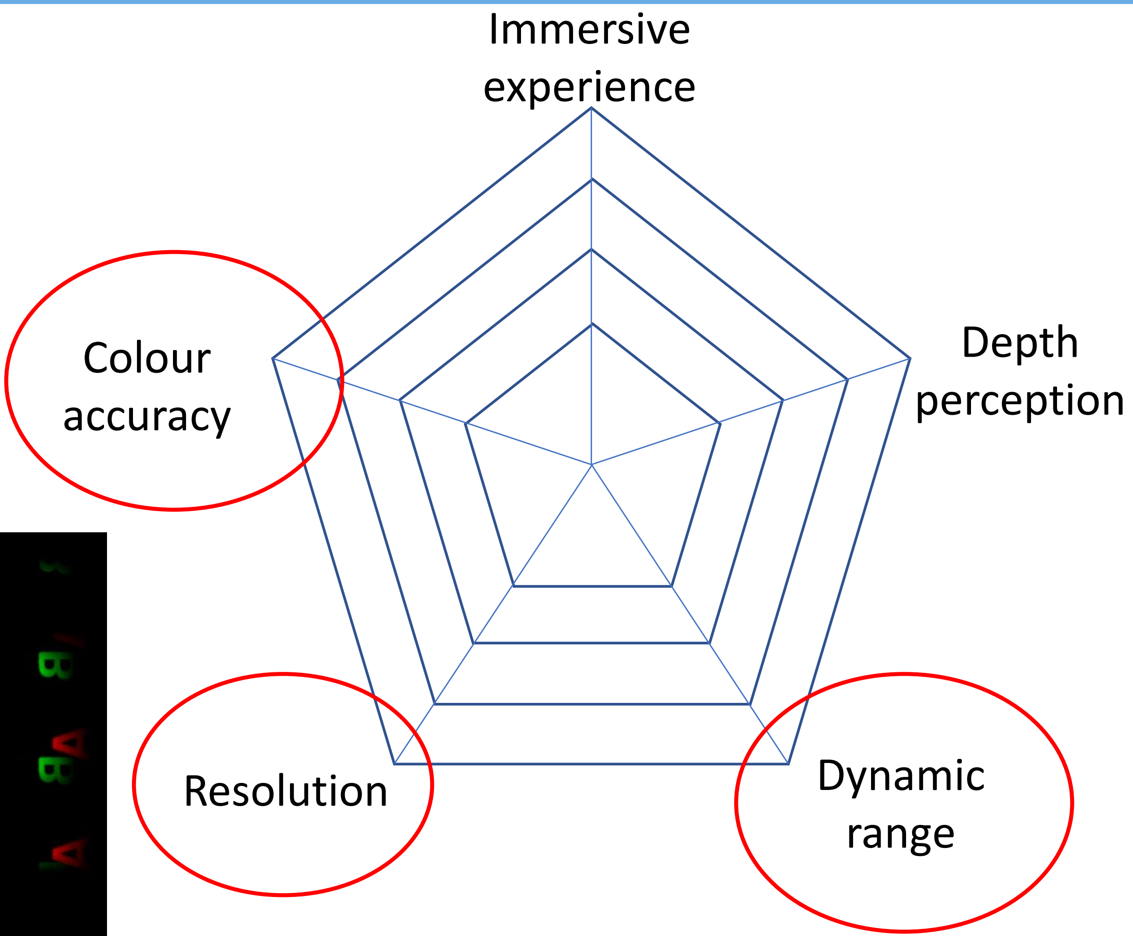
360-degree 3D light field display





Summary

- Visual Turing Test
- Reproducing reality
- Realistic 3D displays
- 360-degree displays
- Vision experiments with novel displays